



Offshore CREYAP Part 2 – final results

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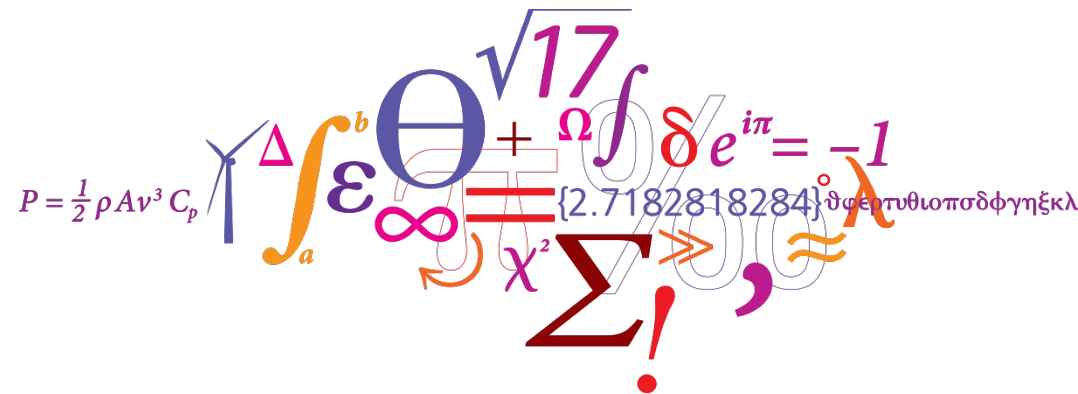
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Offshore CREYAP Part 2 – final results

Niels G Mortensen, Morten Nielsen & Hans E Jørgensen

EWEA Resource Assessment 2015

Helsinki, Finland



Acknowledgements

- DONG Energy Wind Power A/S for Barrow data
- Dong Energy, Iberdrola and Crown Estate for Shell Flats wind data and other information.
- 22 teams from 8 countries; thanks for making the comparison and presentation possible!
- EWEA team for arranging the 2015 Offshore CREYAP Part 2, thanks to Tim Robinson *et al.*

Comparison of Resource and Energy Yield Assessment Procedures

EWEA CREYAP concept

- Industry benchmark
- In-house training and R&D
- Identification of R&D issues

Three issues today

- Wakes and wake modelling
- Yield assessment uncertainties
- Modelled vs observed yields

CREYAP history

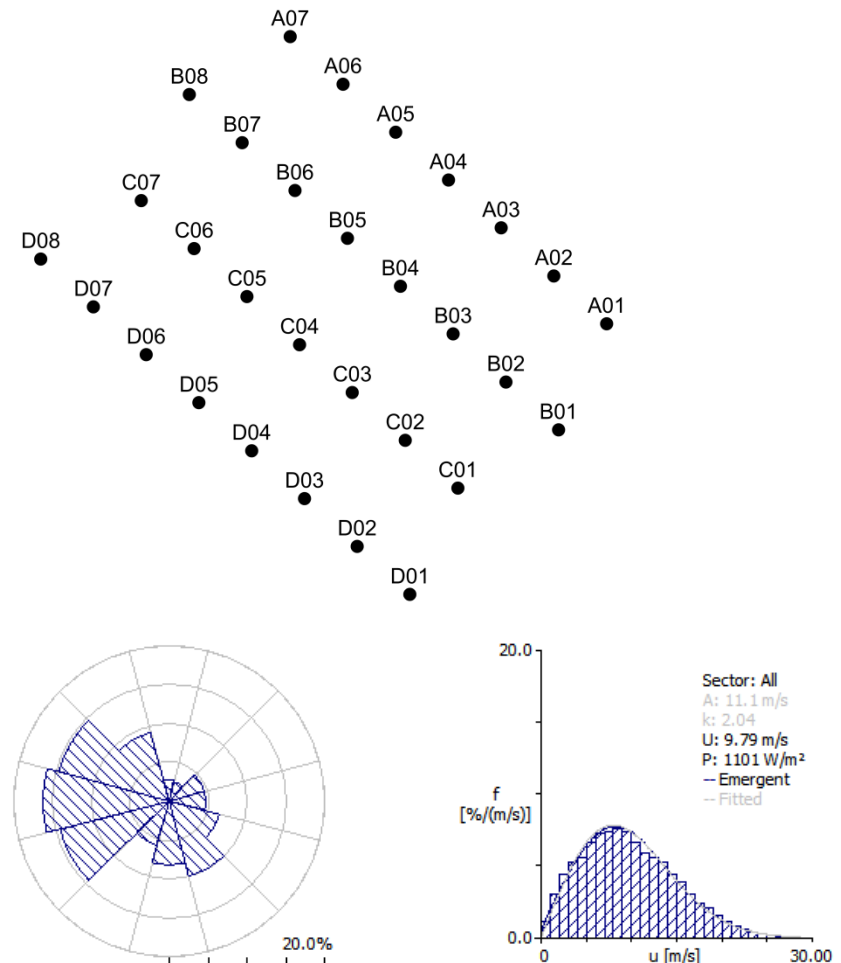
- Onshore Part 1, Bruxelles 2011
 - Scotland W, 28 MW, 37 teams
- Onshore Part 2, Dublin 2013
 - Scotland E, 29 MW, 60 teams
- Offshore Part 1, Frankfurt 2013
 - Gwynt y Môr, 576 MW, 37 teams
- Offshore Part 2, Helsinki 2015
 - Barrow, 90 MW, 22 teams

Summary

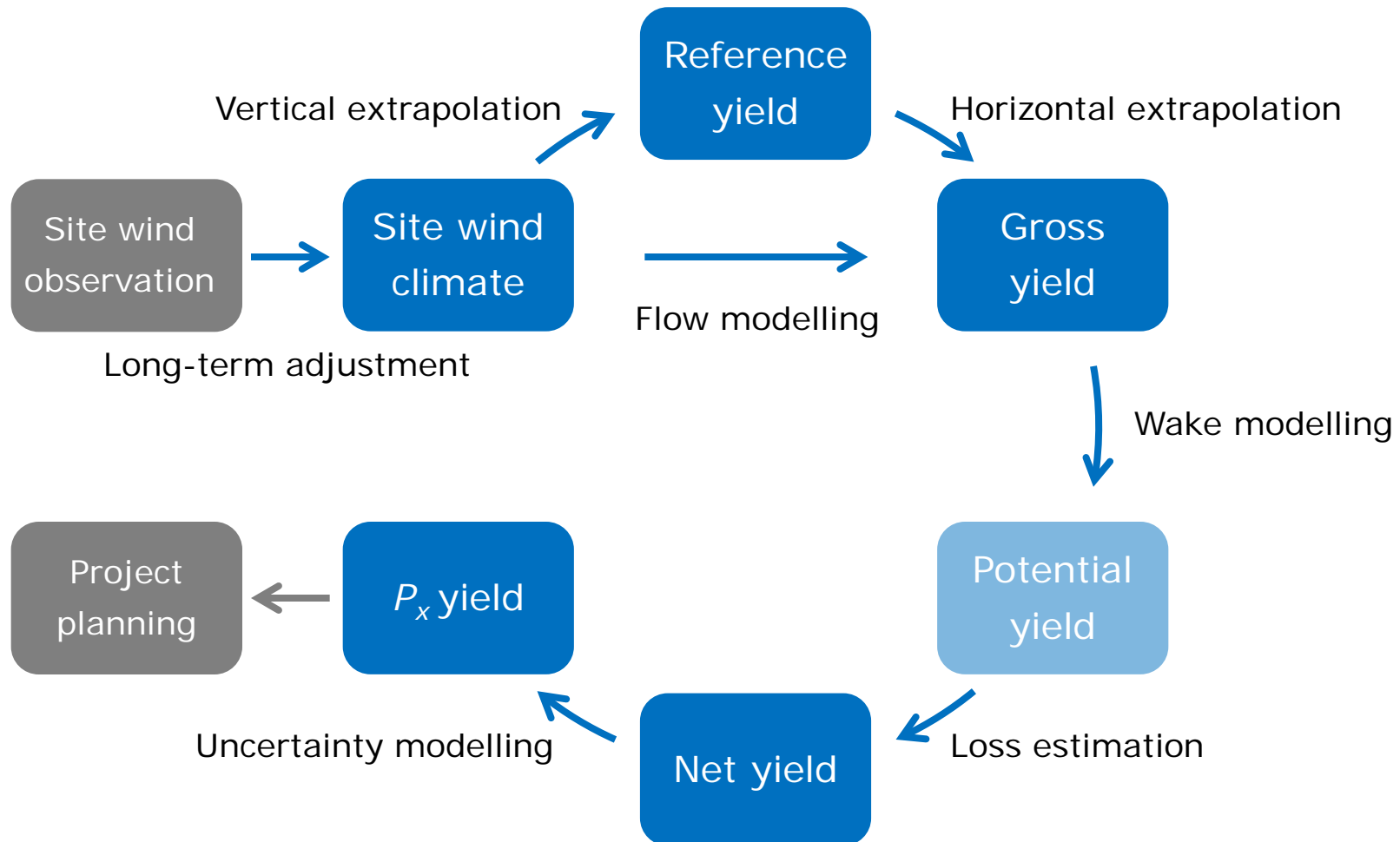
- 156 submissions from 27 countries

Barrow Offshore Wind Farm

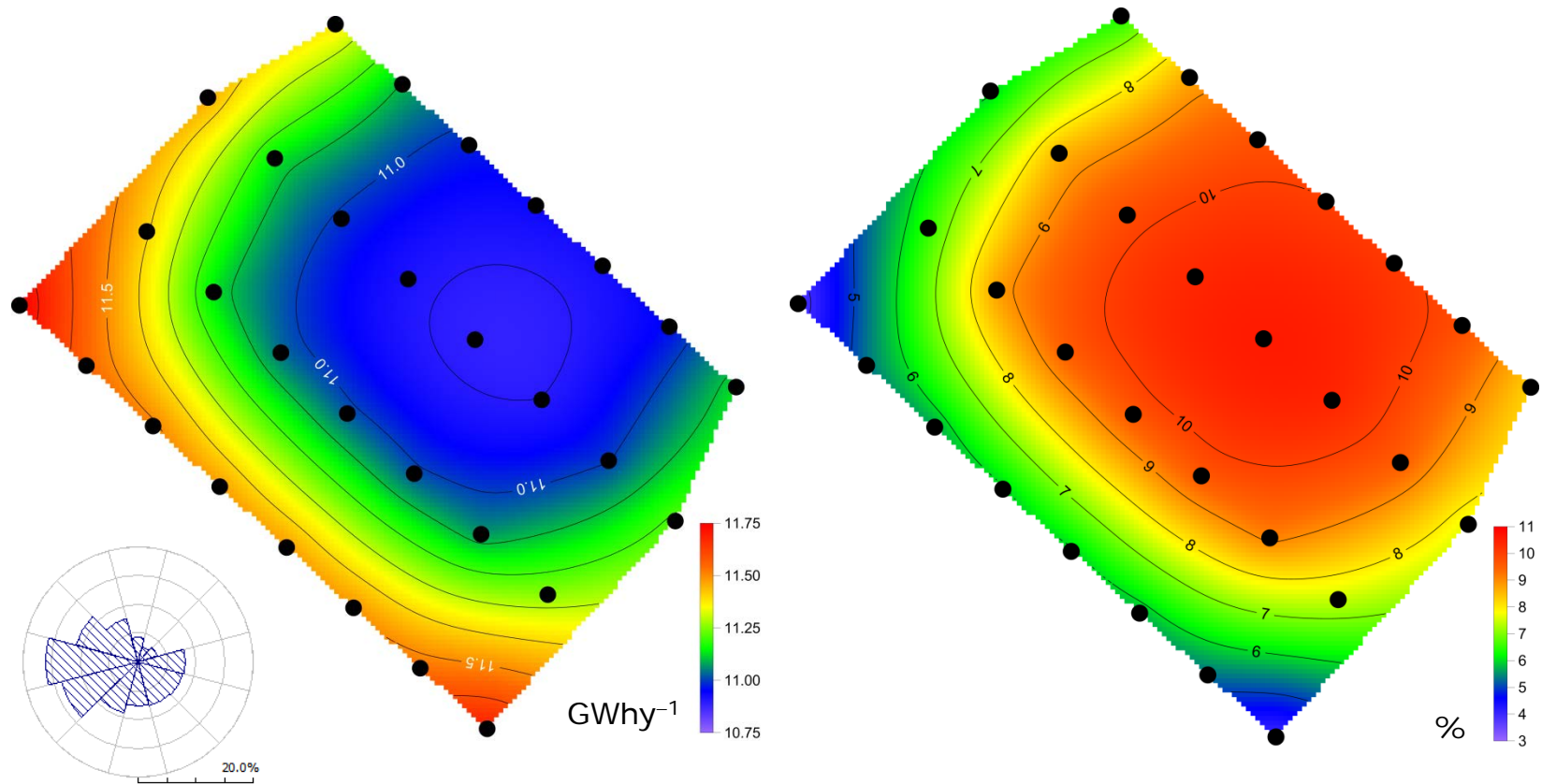
- 30 V90 wind turbines (90 MW)
 - Rated power: 3.0 MW
 - Hub height: 75 m MSL
 - Rotor diameter: 90 m
 - 4 staggered rows, $5.5 \times 8.5 D$
 - Air density: 1.23 kg m^{-3}
 - SCADA: 2008-02 to 2009-01
- Site meteorological masts
 - One 80-m and 50-m mast
 - Wind speed and direction
 - Temperature and pressure
 - Data: 2011-07 to 2012-08
- Auxiliary data
 - MERRA reanalysis 1998-2013
 - Topographical data by choice



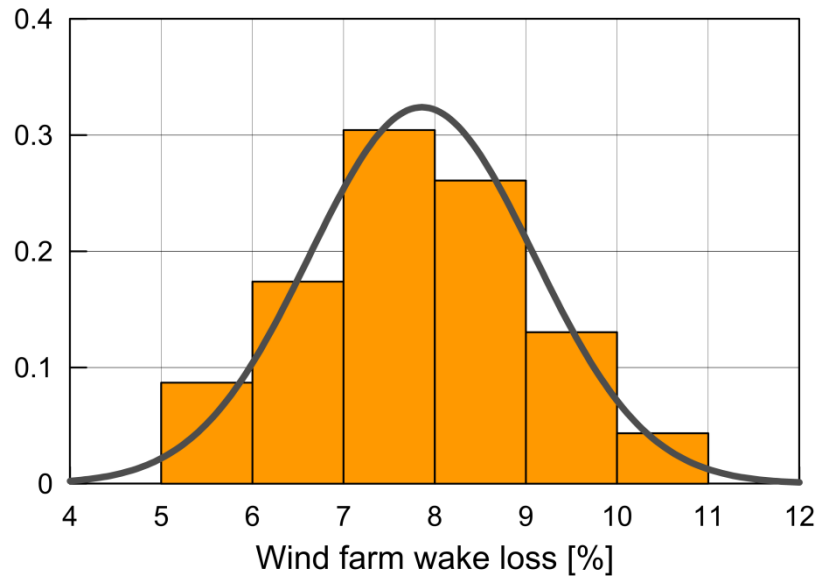
Steps in the energy yield prediction process



Estimated turbine mean yield and wake effect (10 y)



Predicted wind farm wake losses



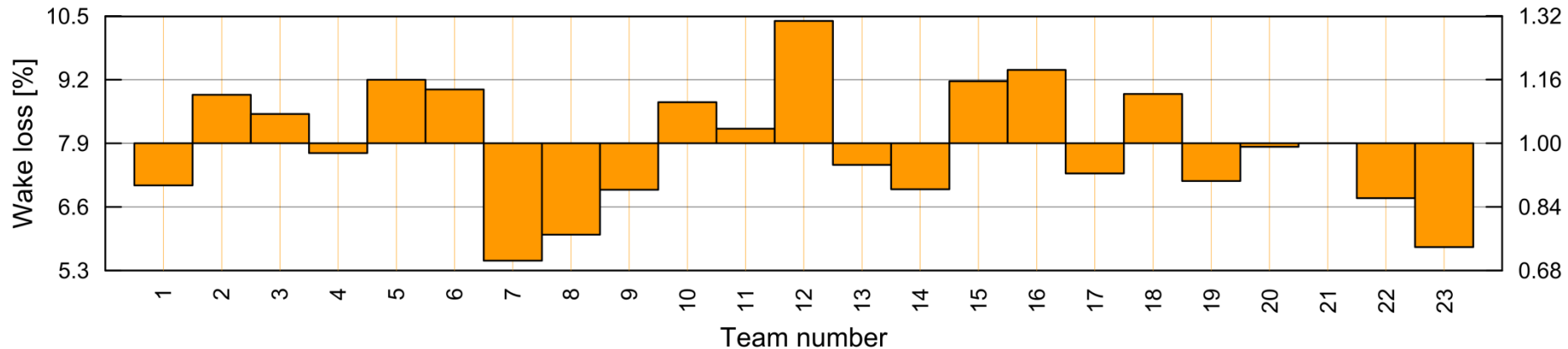
Data points used = 23 (of 23)

Mean wake loss = 7.9%

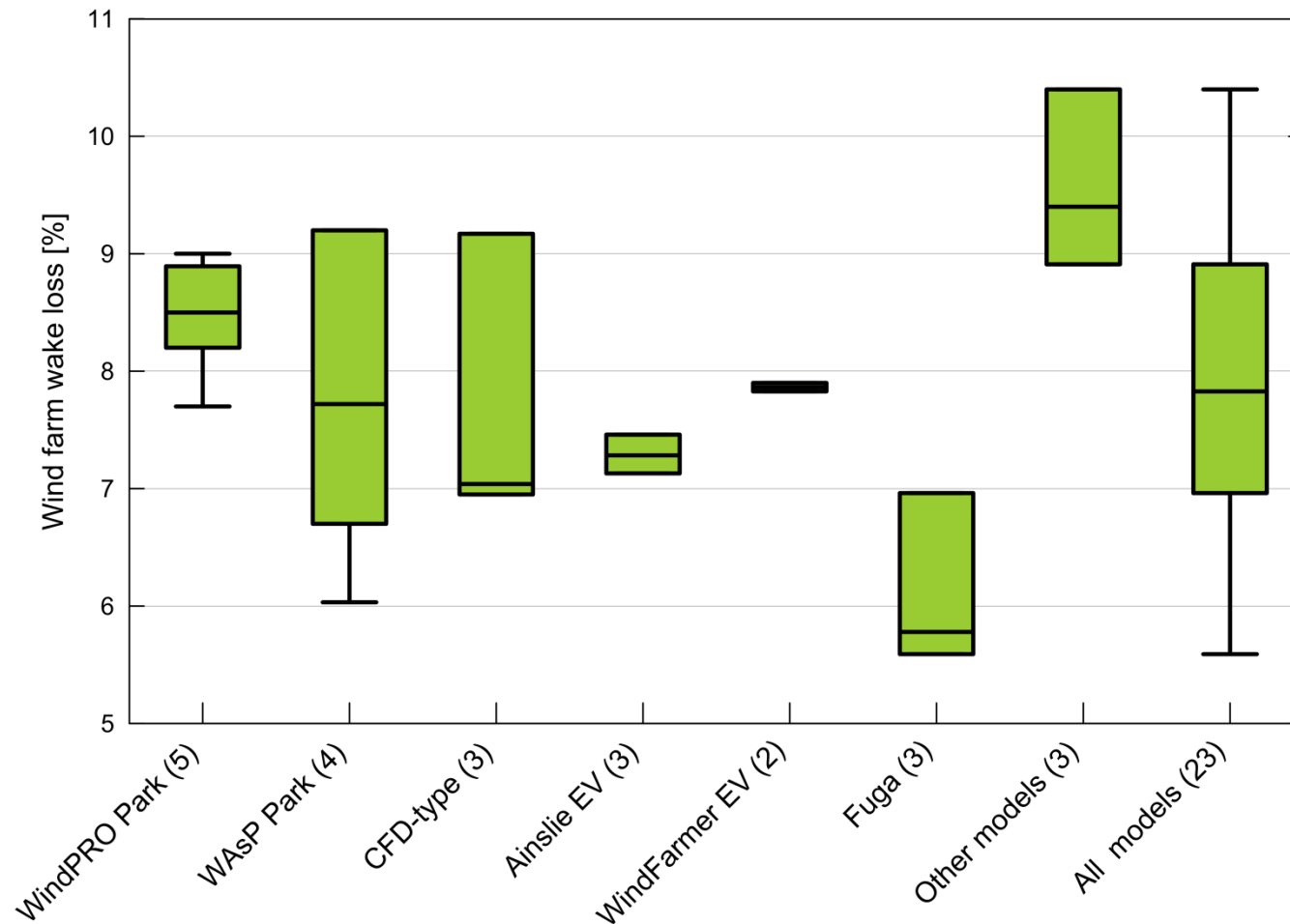
Standard deviation = 1.3%

Coefficient of variation = 16%

Range = 5.5 to 10.4%



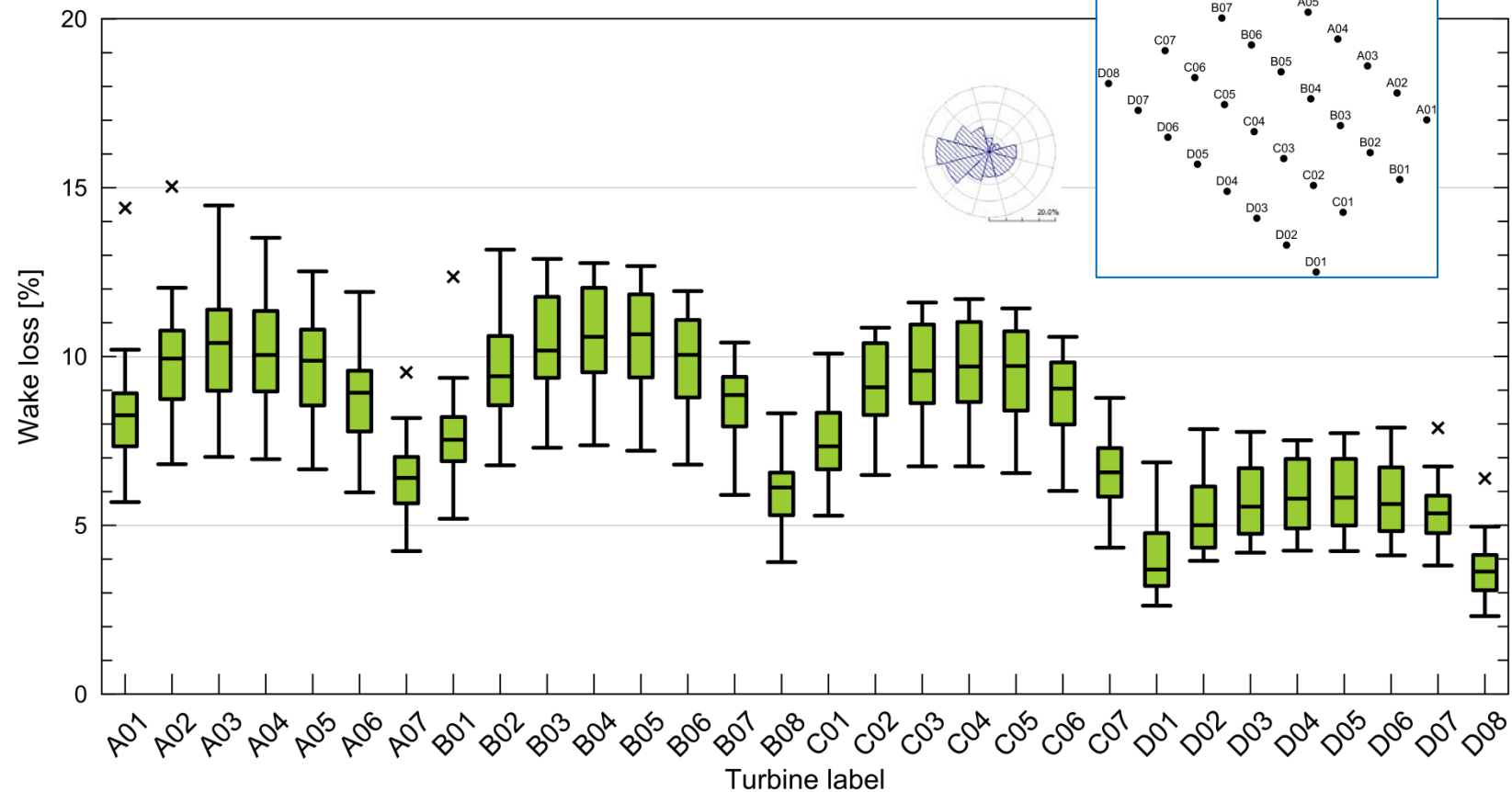
Comparison of wake models



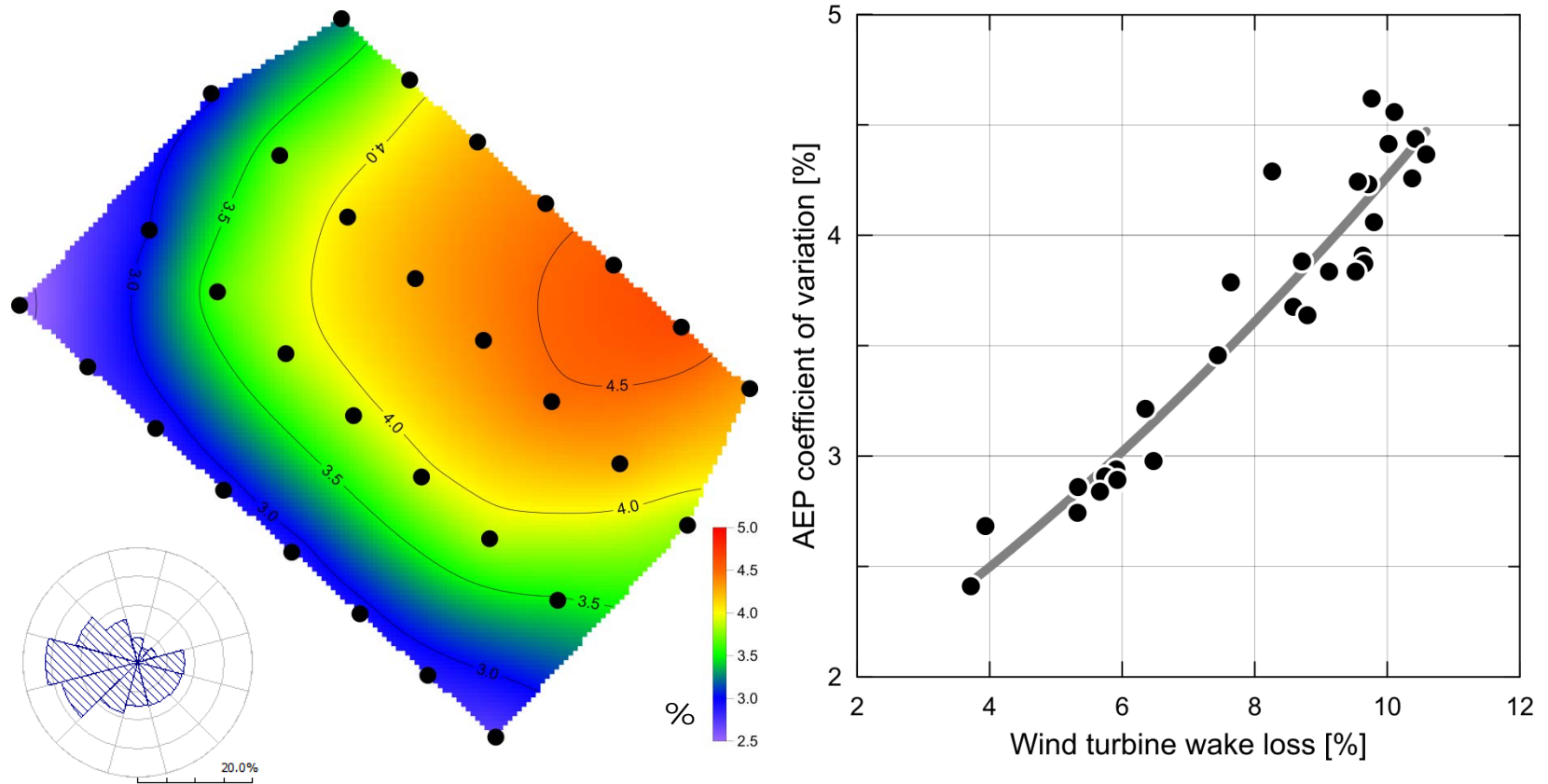
Wake models used

- windPRO Park (N.O. Jensen) (5)
 - $k = 0.04$, offshore settings, ...
- WAsP Park (4)
 - $k = \{0.03, 0.04, 0.05, 0.075\}$
- CFD-type (3)
 - OpenFoam CFDwake, CFD+linear, WindSim WM-1
- Ainslie Eddy Viscosity (3)
 - Quarton, + linearised CFD, +equivalent roughness
- WindFarmer Eddy Viscosity (2)
 - LWF correction, LWF
- FUGA (3)
 - Neutral, stable, unstable
- Other models (3)
 - OpenWind DAWM, Jensen-type+deep array+eff. turbulence, EV

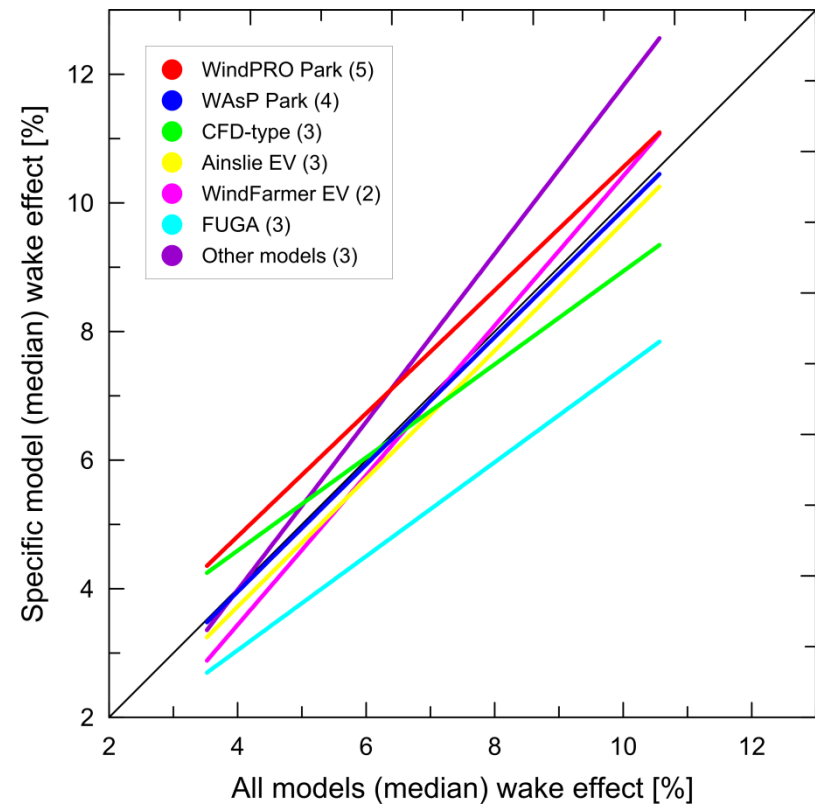
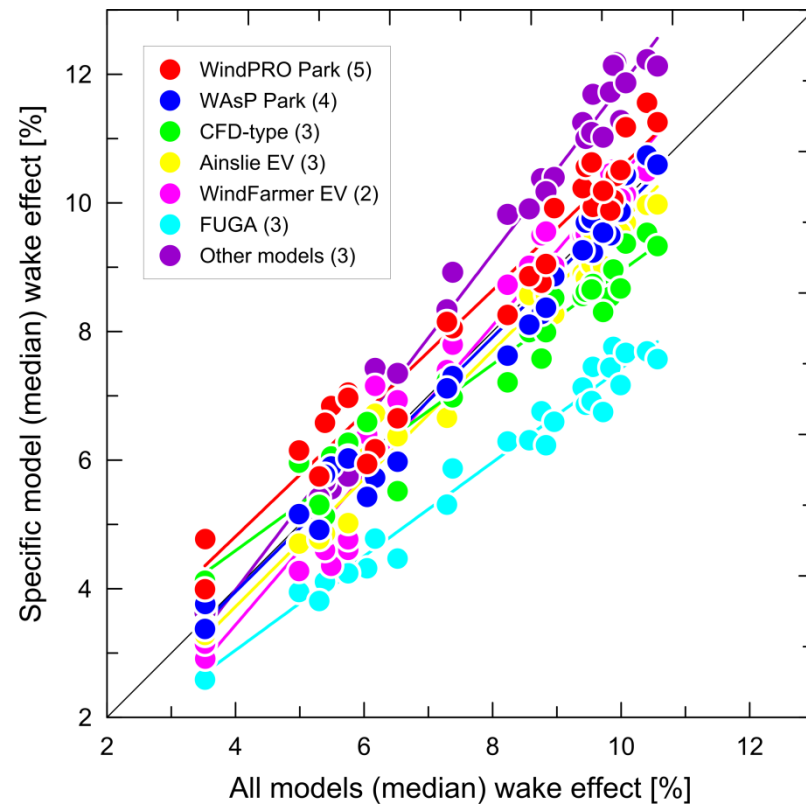
Predicted turbine site wake loss



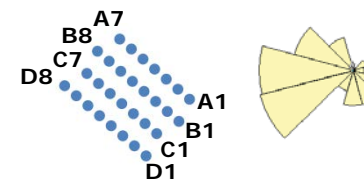
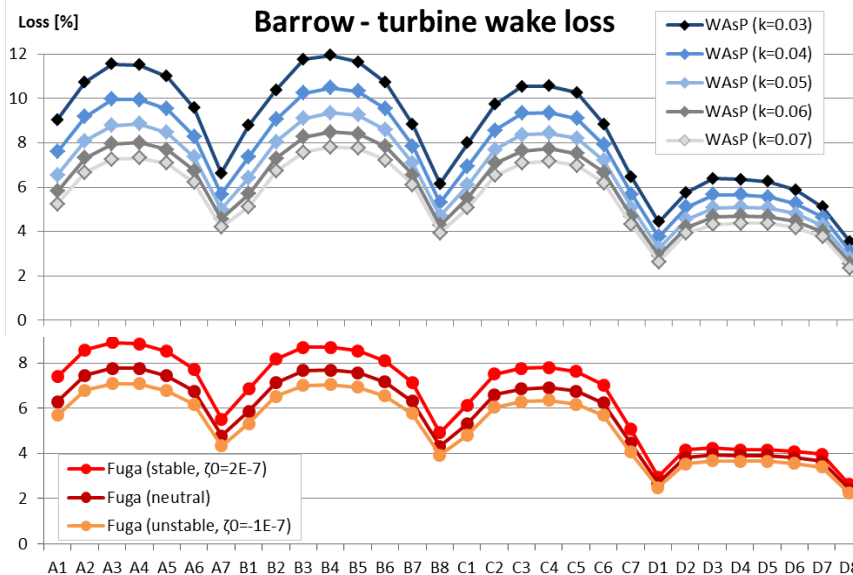
Estimated turbine yields – coefficient of variation



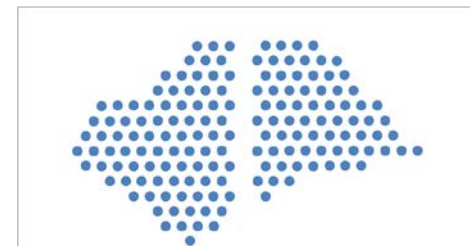
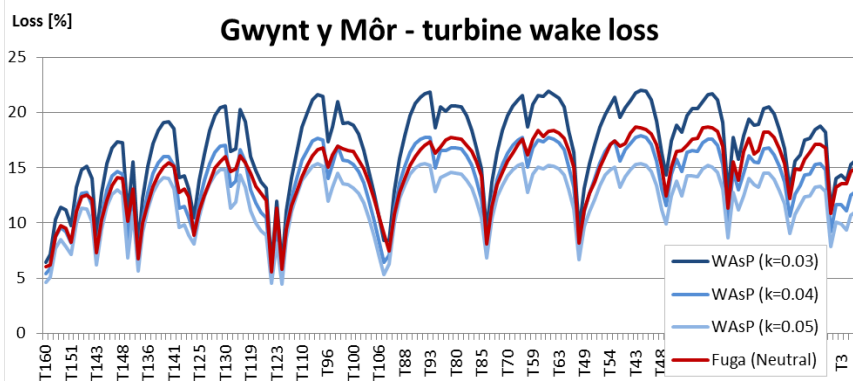
Predicted turbine site wake losses



Sensitivity to WAsP and Fuga input parameters



- Variable input parameters explain spread in wake loss predictions
- Impossible to select universal parameters which will match WAsP and Fuga results for all turbine positions

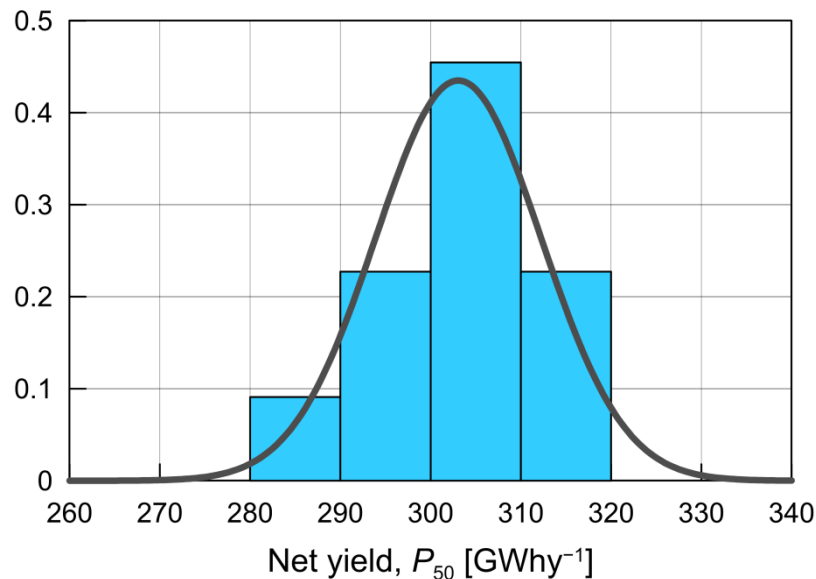


Wake modelling uncertainty (CREYAP 1-4)

Wind farm	Size	Layout	Wake loss	Uncertainty
Onshore Hilly	28 MW 14 WTG	Irregular 3.7-4.8 <i>D</i>	6.1%	13%
Onshore Complex	29 MW 22 WTG	Irregular 4-5 <i>D</i>	10.3%	18%
Offshore Gwynt y Môr	576 MW 160 WTG	Regular 6-7 <i>D</i>	14.3%	37%
Offshore Barrow	90 MW 30 WTG	4 staggered 5.5 × 8.5 <i>D</i>	7.9%	16%
10 offshore* DONG 2015	90-630 MW 30-175 WTG	various	n/a	16%

* N.G. Nygaard, EWEA Offshore 2015

Net energy yield of wind farm, P_{50} (10 y)



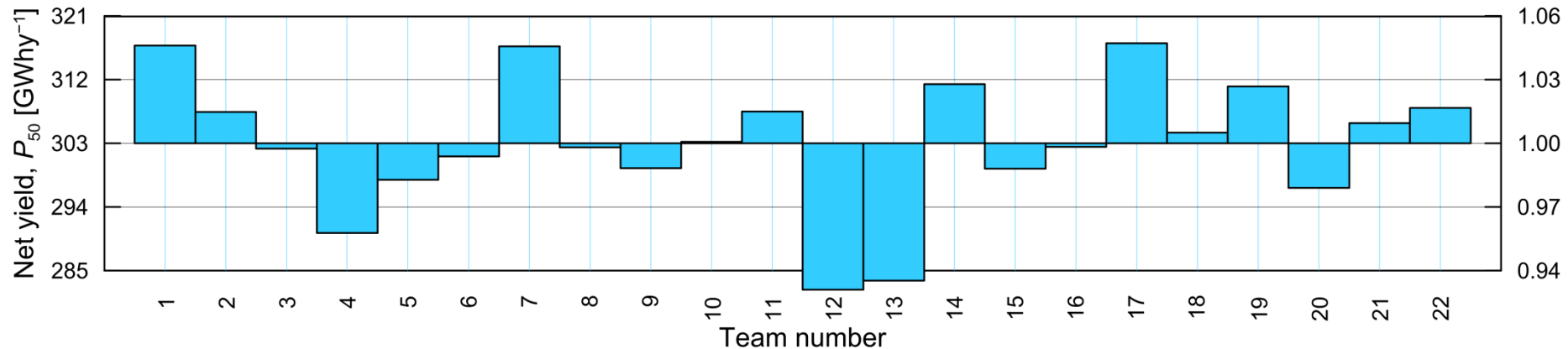
Data points used = 22 (of 22)

Mean net yield = 303 GWh $^{-1}$

Standard deviation = 9.4 GWh $^{-1}$

Coefficient of variation = 3.1%

Range = 282 to 317 GWh $^{-1}$

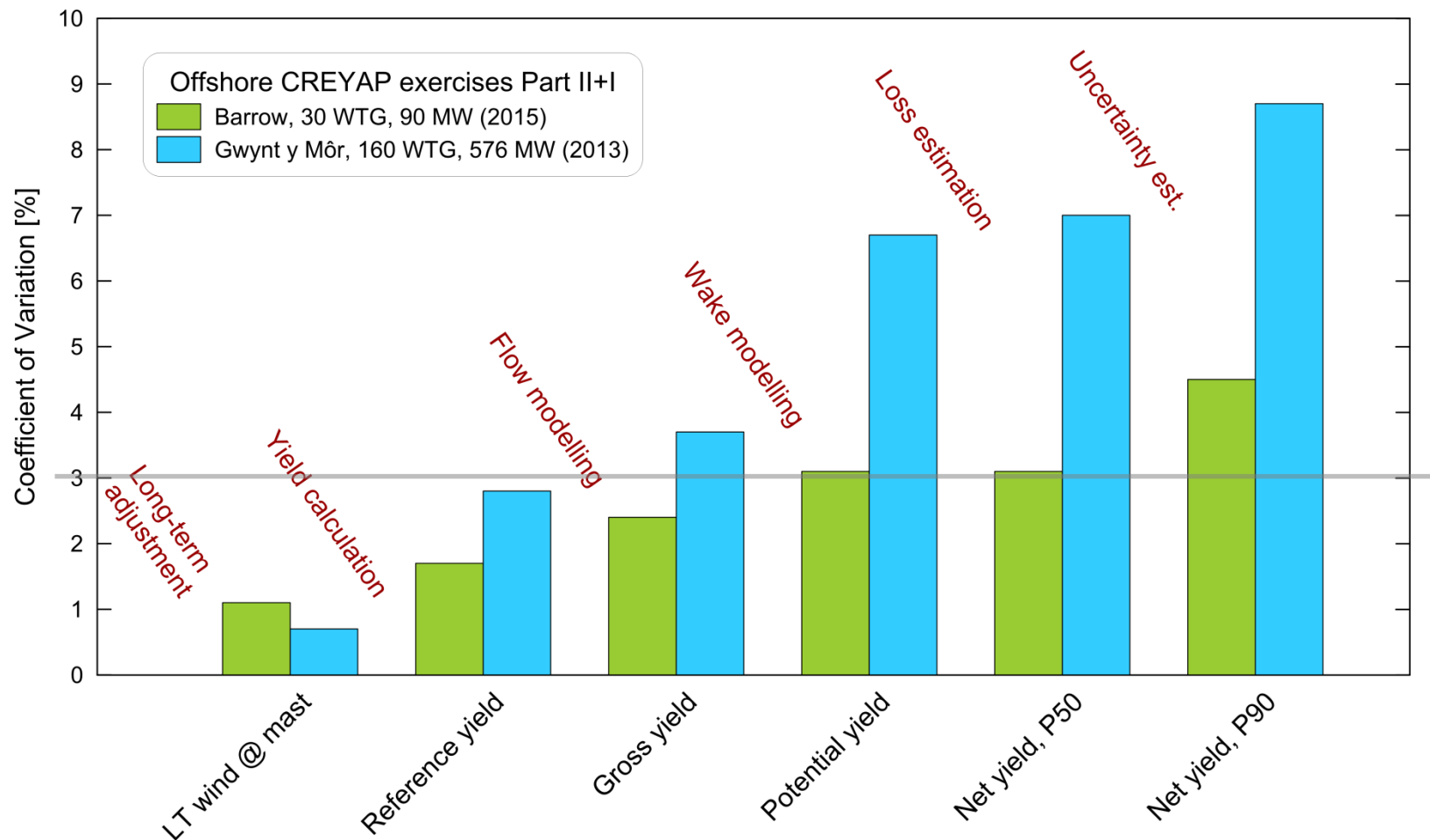


Wind farm key figures (10-y estimates)

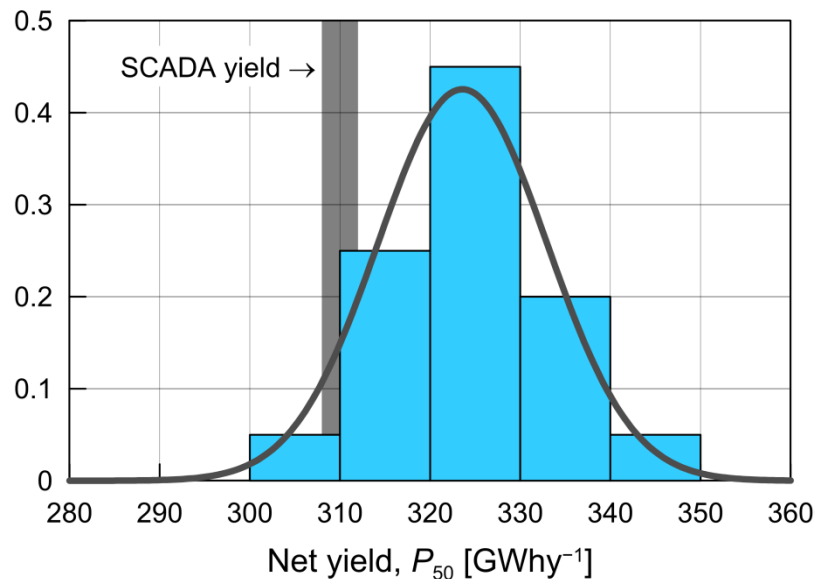
Barrow (10 y)		Mean	σ	CV*	Min	Max
Gross yield	GWh	366	8.9	2.4	338	377
Wake loss	%	7.9	1.3	16.0	5.5	10.4
Potential yield	GWh	334	10.3	3.1	311	350
Technical losses	%	9.3	0.1	1.0	9.2	9.6
Net yield P_{50}	GWh	303	9.4	3.1	282	317
Uncertainty	%	9.7	2.3	23.4	6.1	13.7
Net yield P_{90}	GWh	267	12.1	4.4	245	282

* Coefficient of Variation in per cent

Spread for different steps in the prediction process



Comparison of predicted to observed P_{50} (1 year)



Data points used = 20 (of 22)

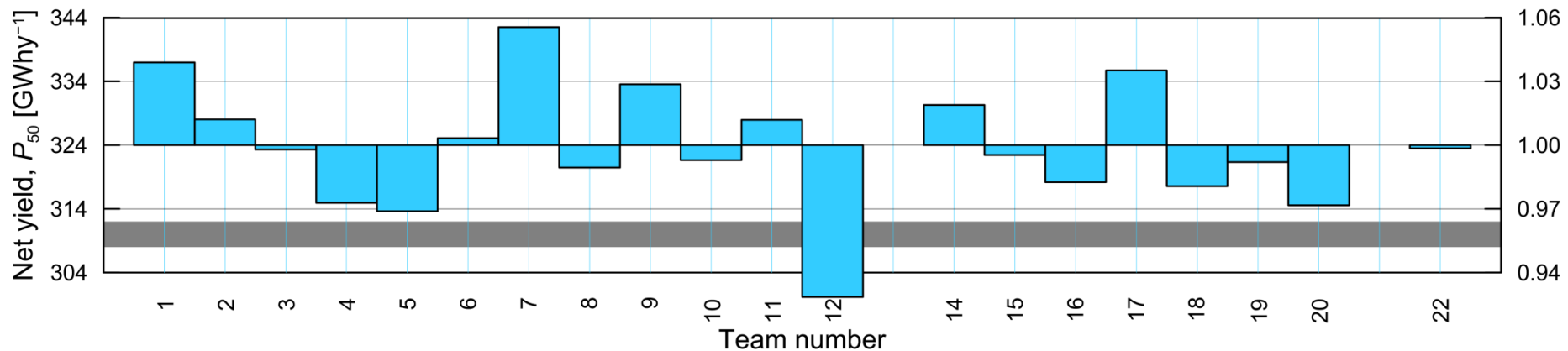
Mean predicted $P_{50} = 324 \text{ GWhy}^{-1}$

Standard deviation = 9.6 GWhy^{-1}

Coefficient of variation = 3.0%

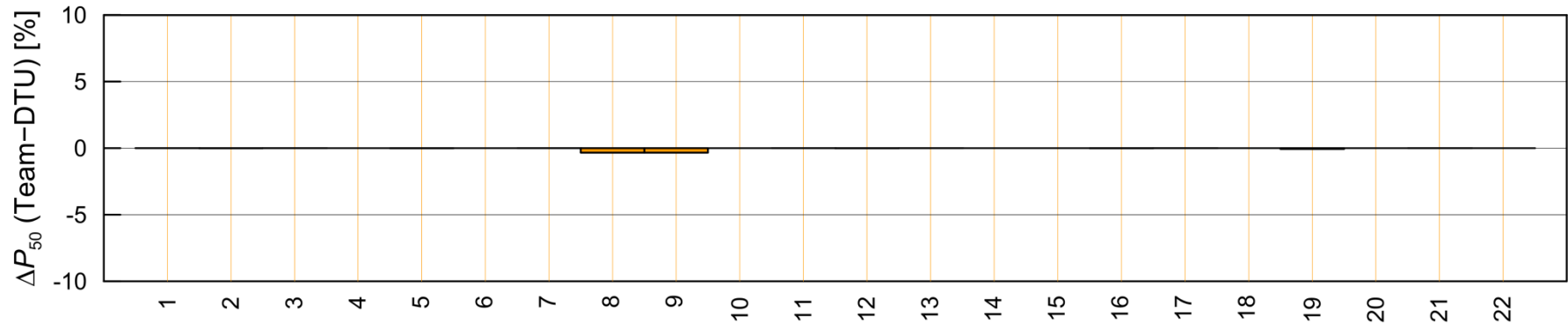
Range = 300 to 343 GWhy⁻¹

Prediction bias = +4%



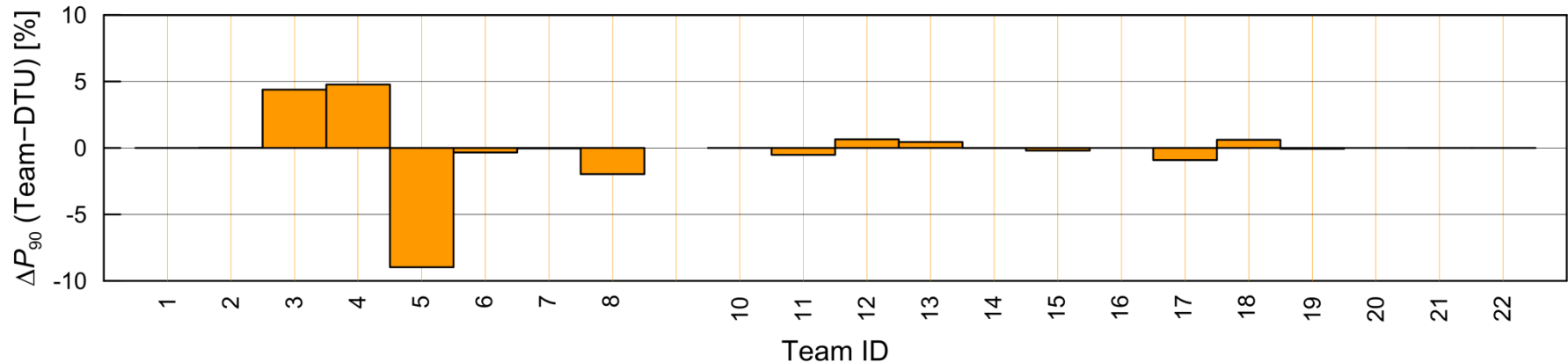
Quality assurance of submitted spreadsheets

Cross-check of P_{50} : team results compared to DTU calculation from team values.



- Net AEP (P_{90}) = Net AEP (P_{50}) - 1.282 × [uncertainty estimate]

Cross-check of P_{90} : ¾ of the teams agree with DTU, but ¼ get a different result!



Sensitivity analyses for Barrow

Offshore datums and transition piece	Input change	AEP change in %
• Met. mast height	MSL → HAT	+0.9
• Wind turbine hub height	MSL = HAT – 5 m	–1.1
Modelling parameter (examples)		
• Wake decay parameter k in Park	0.01 in k	0.7
• Stability settings in FUGA	1/1000 in $1/L$	0.5
Wind climatology		
• Calibration of anemometer	1% in U	1.3
• Long-term correlation	1% in U	1.3
Power production estimation		
• Air density estimation	1% in ρ	0.6
• Power curve / turbine specification	several	???
Observed production statistics		
• Independent calculations		1.3

Summary and conclusions

- Long-term adjustment (applied twice)
 - Average effect = 5.7%, spread = 1.2%
- Wake modelling
 - Average wind farm wake effect = 7.9%, spread = 16%
 - Wake modelling spread increases with depth into wind farm
 - Wake model, version, and settings should all be specified
- Modelled vs observed 1-y yields
 - Estimated = 104% of observed, spread = 3%
 - Uncertainty of predictions within TPWind vision
 - Measured yield has an uncertainty too
- CREYAP results seem to improve over time
 - No or fewer outliers in present study
 - Uncertainty $\sim 3\%$ for net yield (P_{50})
 - But uncertainty calculations still not good enough...

Future work

- Summary and reporting on first four CREYAP exercises
 - Hilly, moderately complex and offshore covered so far
 - Abstract submitted for EWEA 2015
- Future CREYAP exercises
 - Wind resource and energy yield assessment
 - Steep or forested terrain, tall turbines, ...
 - Wind conditions and site suitability
- Comments, suggestions and ideas
 - EWEA: Lorenzo Morselli Lorenzo.Morselli@ewea.org
 - DTU: Niels G Mortensen nimo@dtu.dk
- And, as allways...
 - High-quality wind farm data in high demand for future studies!

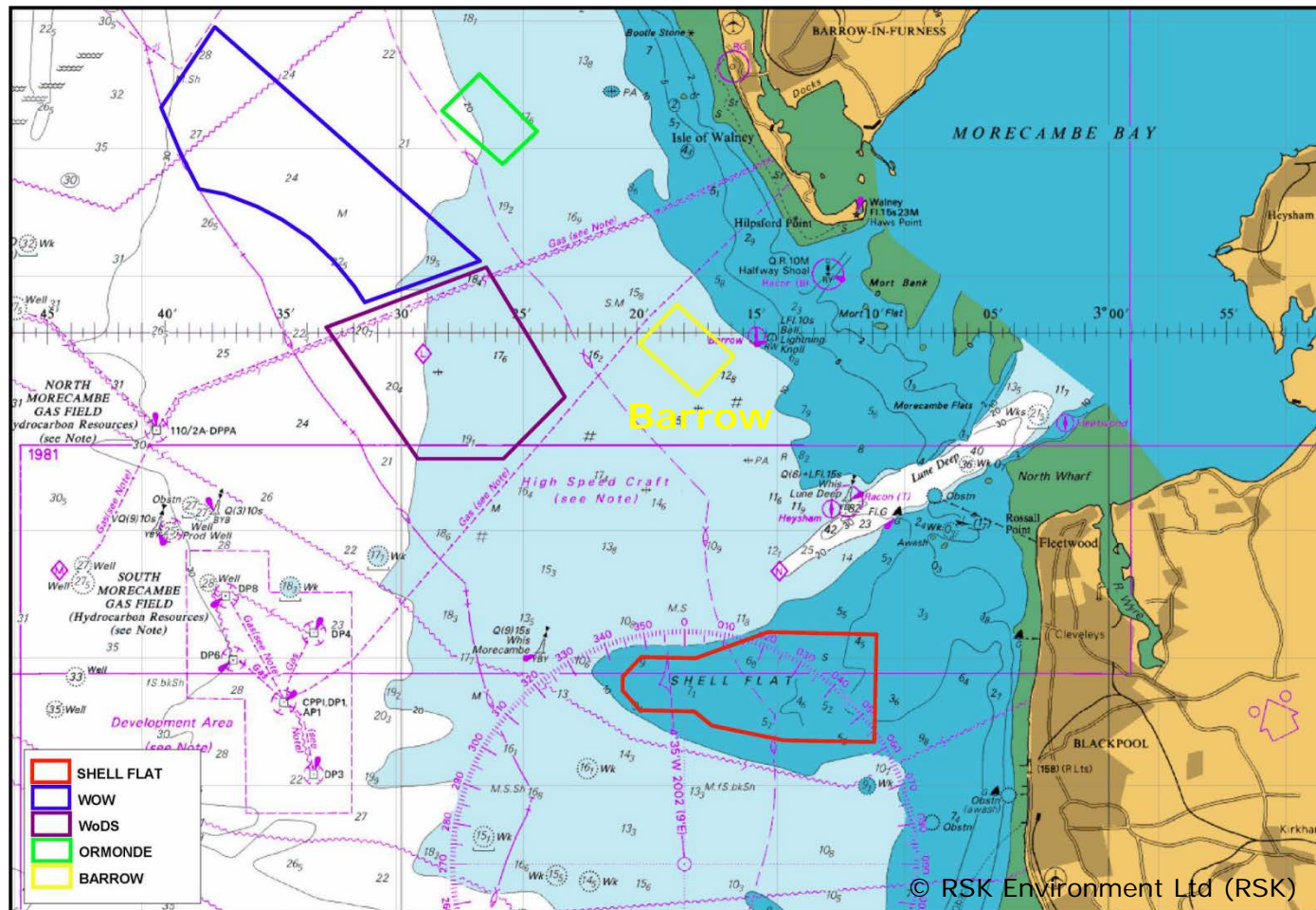
A photograph of an offshore wind farm at sunset. The sky is a gradient of blue and orange, and the sea is dark blue. Several wind turbines are visible, with the largest one in the foreground on the left. The text "Thank you for your attention!" is written in white, italicized font in the upper right area of the image.

Thank you for your attention!

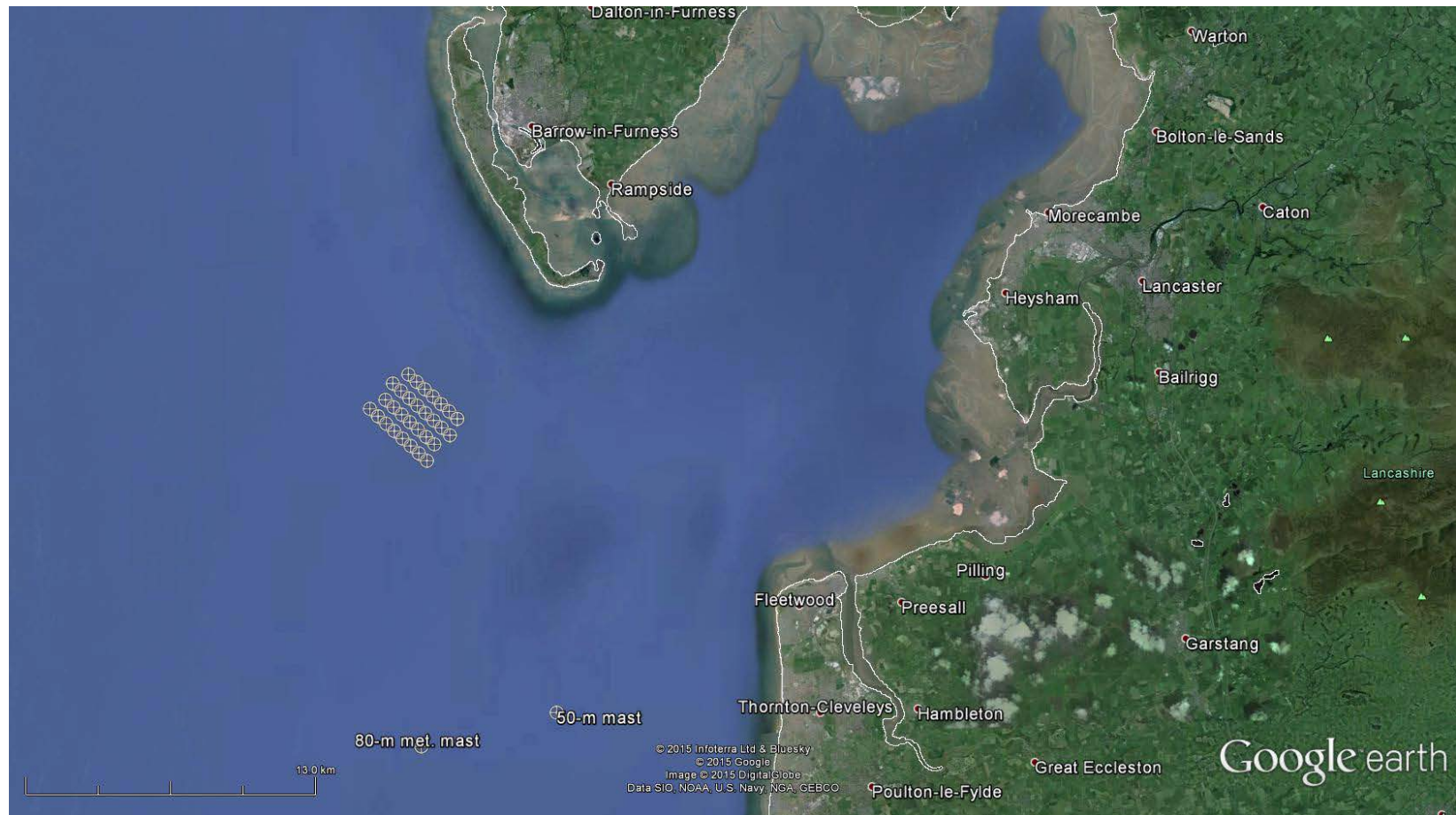
Who submitted results?

- 20 organisations (22 teams) from 8 countries submitted results
 - Belgium, Denmark, Germany, India, Norway, Spain, UK, US
- Names of organisations
 - AWS Truepower LLC, Barlovento Recursos Naturales, CENER, CIRCE, COWI A/S, Deutsche WindGuard, DONG Energy, DTU Wind Energy, Mott MacDonald, Mytrah Energy (India) Ltd, Natural Power, OST Energy, RES, ScottishPower Renewables – Iberdrola, Senvion SE, UL International GmbH (DEWI), Wind Prospect Ltd, WIND-consult GmbH, WindSim AS, YCON BVBA

Barrow offshore wind farm setting



Barrow offshore wind farm setting



Data analysis & presentation

Data material

- Result spreadsheets from 22 teams

Data analysis

- Quality control and reformatting
- Consistent calculations (errors, loss factors)
- Calculation of missing numbers – but no comprehensive reanalysis!

Data presentation

- Comparison of methods and models
 - Non-parametric box-whisker plot
 - Statistics (median, quartiles, IQR)
- Overall distribution of all results
 - Normal distribution fitted to the results
 - Statistics (mean, standard deviation, coefficient of variation)
- Team results for each parameter (see appendix)

Offshore CREYAP II results in two parts

Long-term comparisons (10 y)

- Observed wind climate
- Observed turbulence
- Long-term adjustment
- Reference yield
- Gross yield
- Wake effects
- Net yield P50
- Uncertainty estimates
- Net yield P90
- Per-turbine results

- Team characteristics
- Methodology information

Predicted vs observed yields (1 y)

- Reference yield
- Potential yield
- Array efficiency
- Net P50 (losses given)

- SCADA calculation
 - Sum of WTG power readings
 - Curtailment correction
 - Availability correction to 100%
 - Two independent calculations
 - Checked with sub-station meter

Comparisons of results and methods {definitions}

1. LT wind @ X m (mast) = Measured wind \pm [long-term adjustment]
 - comparison of **long-term adjustment methods**
2. LT wind @ Y m (hub height) = LT wind @ X m + [wind profile effects]
 - comparison of **vertical extrapolation methods**
3. Gross AEP = Reference AEP \pm [terrain effects]
 - comparison of **flow models**
4. Potential AEP = Gross AEP – [wake losses]
 - comparison of **wake models**
5. Net AEP P_{50} = Potential AEP – [technical losses]
 - comparison of **technical losses estimates**
6. Net AEP $P_{90} = P_{50} - 1.282 \times$ [uncertainty estimate]
 - comparison of **uncertainty estimates**
7. Comparison to teams average AEP – **spread** and **bias**

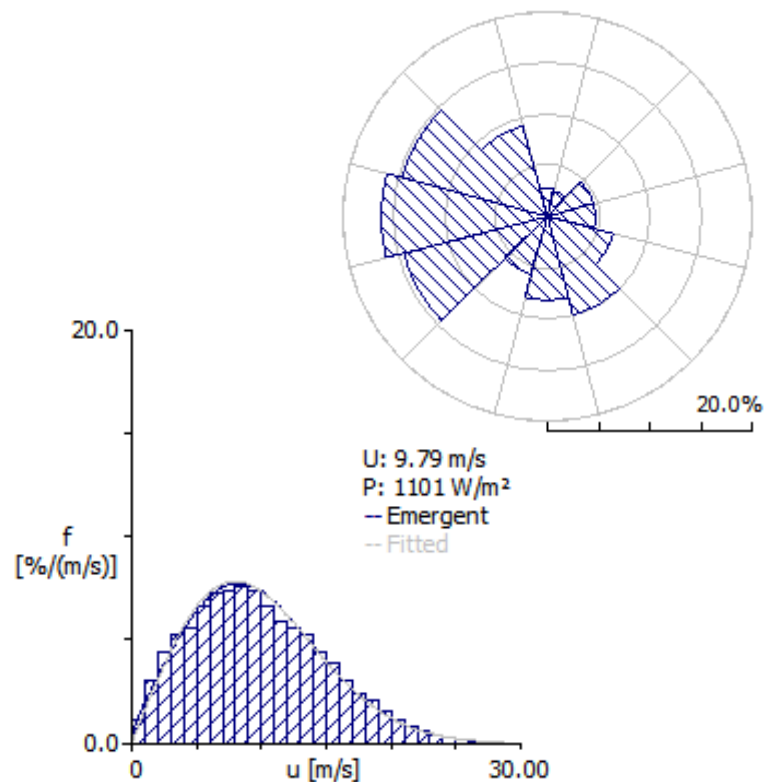
Comparisons of results and methods {notes}

- Long-term correlation methods
 - MCP on site and MERRA data, no adjustment factors given by teams
- Vertical extrapolation methods
 - Wind shear exponent not important here
- Flow modelling
 - Terrain effects not reported explicitly by teams
- Wake modelling
 - Illustrated in presentation in several ways
- Systematic technical losses estimates
 - Losses prescribed by exercise
- Uncertainty estimates/modelling
 - Uncertainty components in prescribed categories

Wind-climatological inputs

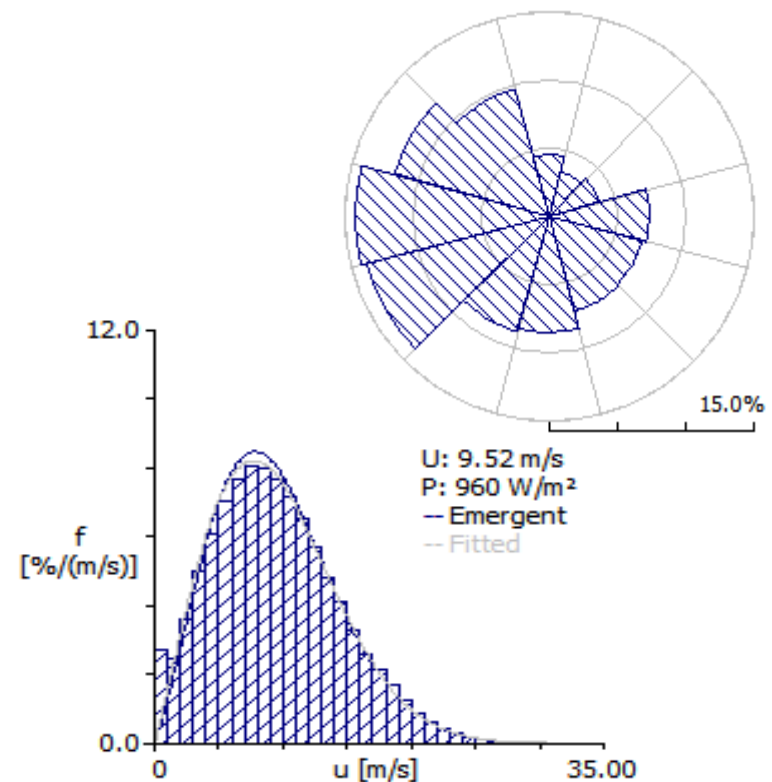
Site meteorological mast

- 1 y of 10-min data (2011-12)

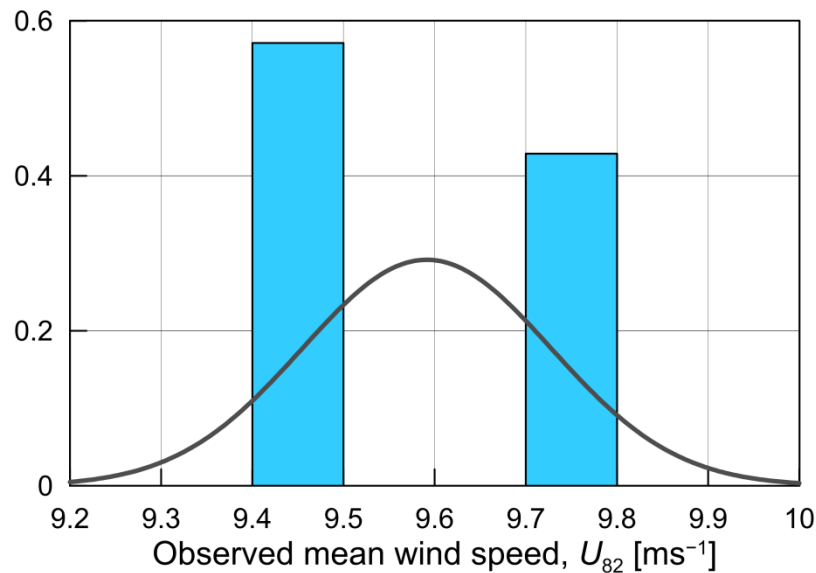


MERRA reanalysis data

- 16 y of hourly data (1998-2013)



Observed wind speed @ 82 m



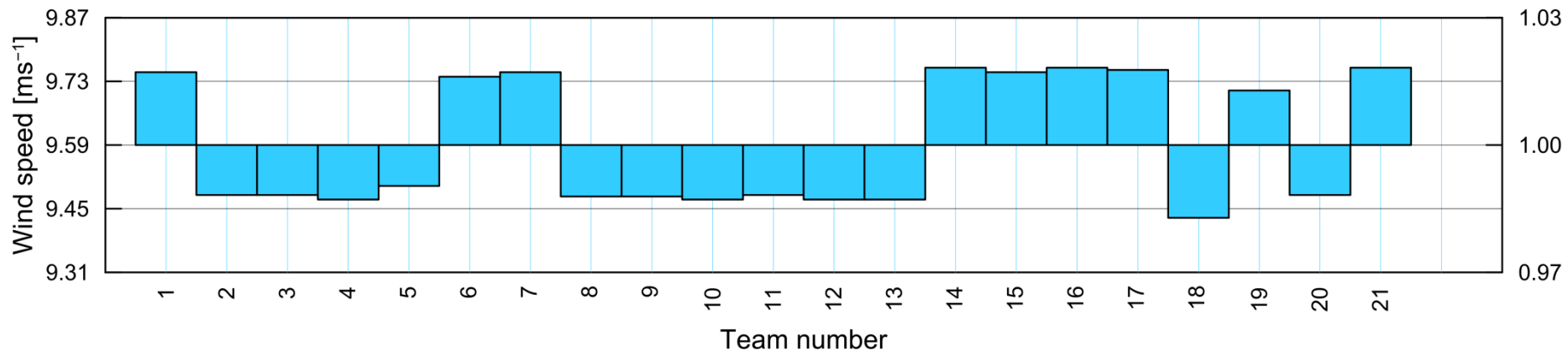
Data points used = 21 (of 22)

Mean wind speed = 9.59 ms^{-1}

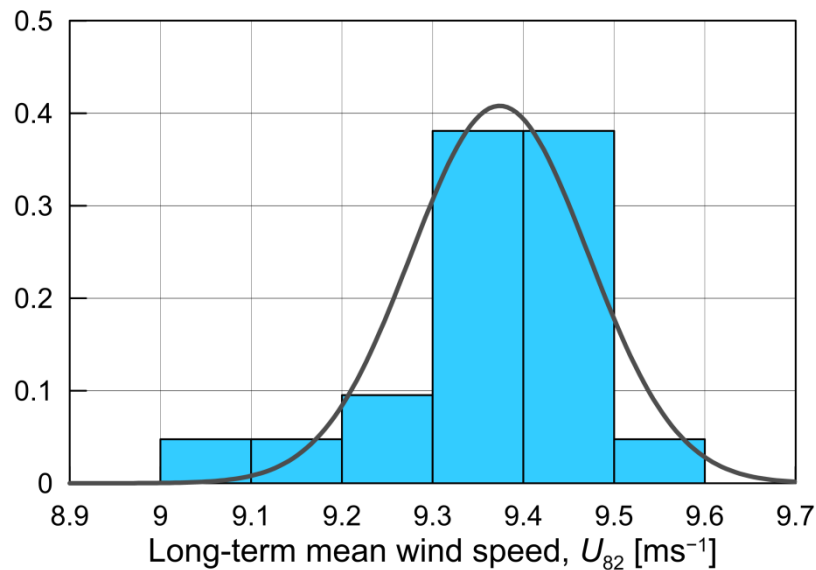
Standard deviation = 0.14 ms^{-1}

Coefficient of variation = 1.5%

Range = 9.43 to 9.76 ms^{-1}



Long-term wind speed @ 82 m



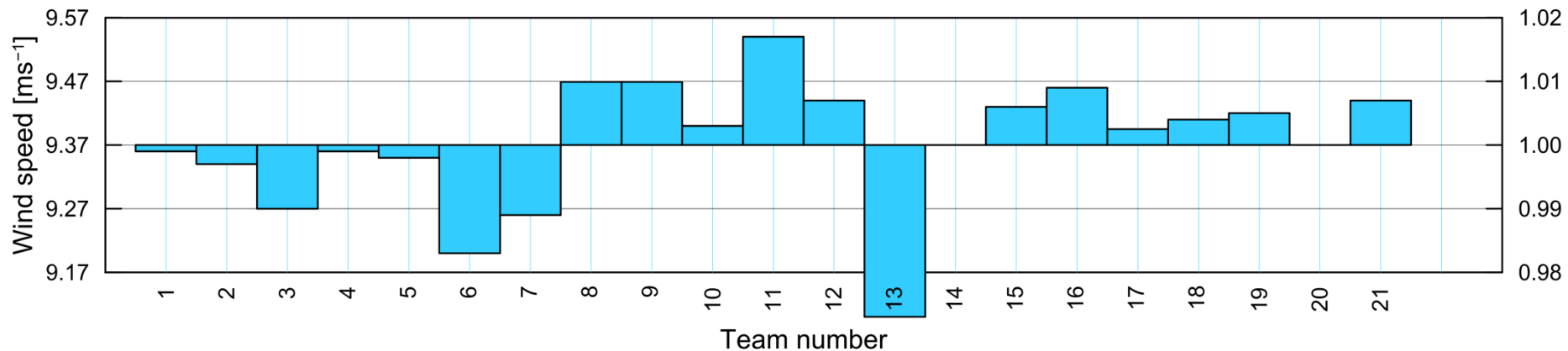
Data points used = 21 (of 22)

Mean wind speed = 9.37 ms^{-1}

Standard deviation = 0.10 ms^{-1}

Coefficient of variation = 1.1%

Range = 9.10 to 9.54 ms^{-1}



Wind speed uncertainty @ 82 m

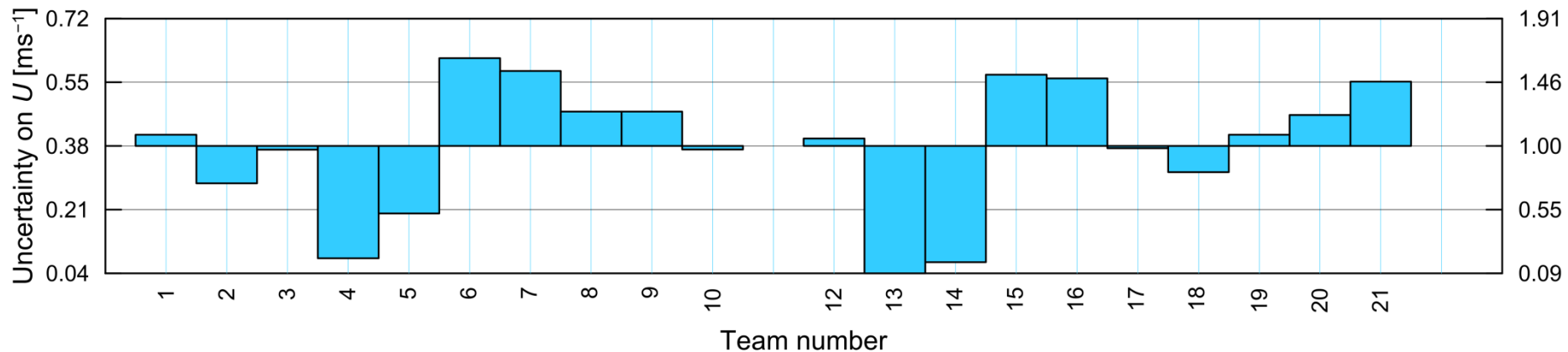
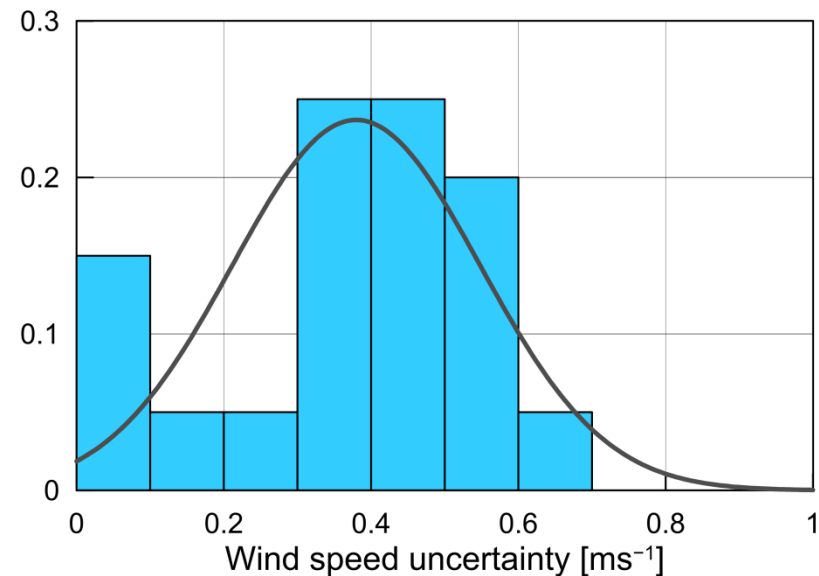
Data points used = 20 (of 22)

Mean uncertainty = 0.38 ms^{-1}

Standard deviation = 0.17 ms^{-1}

Coefficient of variation = 46%

Range = 0.04 to 0.61 ms^{-1}



Turbulence intensity @ 82 m

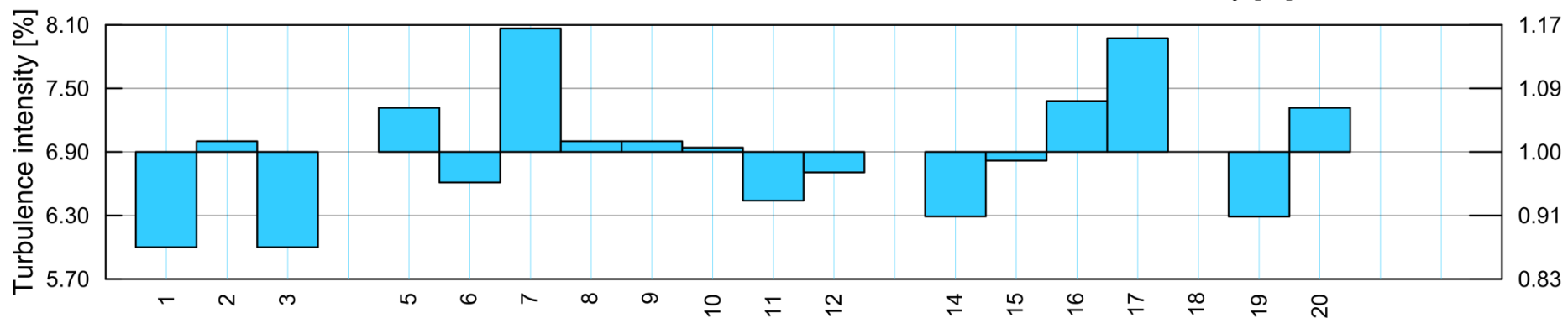
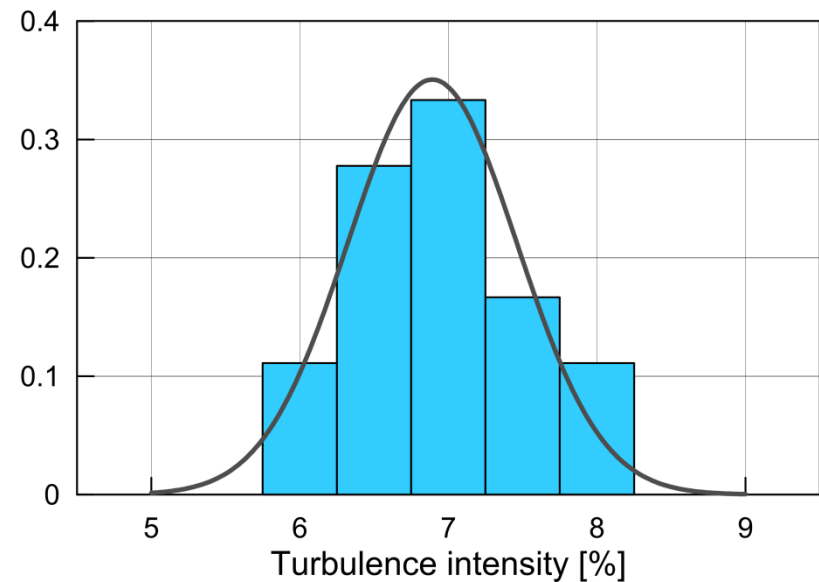
Data points used = 18 (of 22)

Mean turbulence intensity = 6.9%

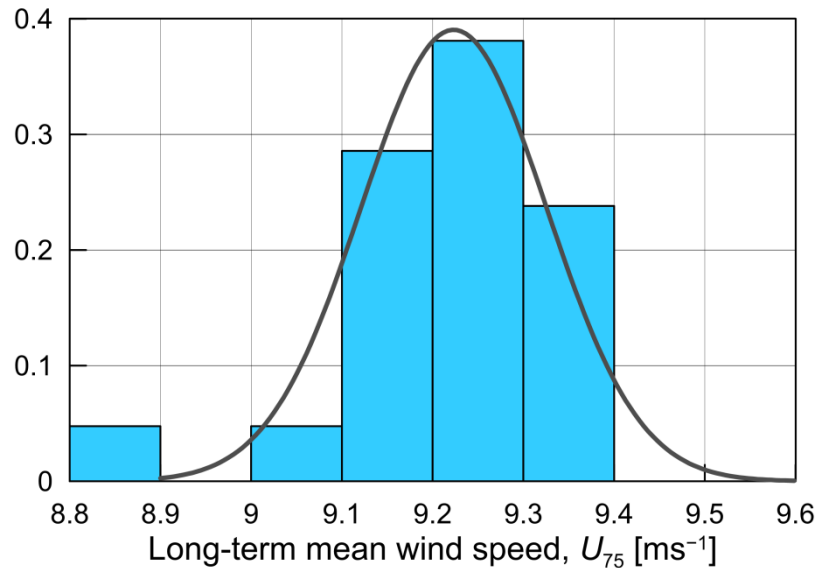
Standard deviation = 0.6%

Coefficient of variation = 8.5%

Range = 6.0 to 8.1%



Long-term wind speed @ 75 m



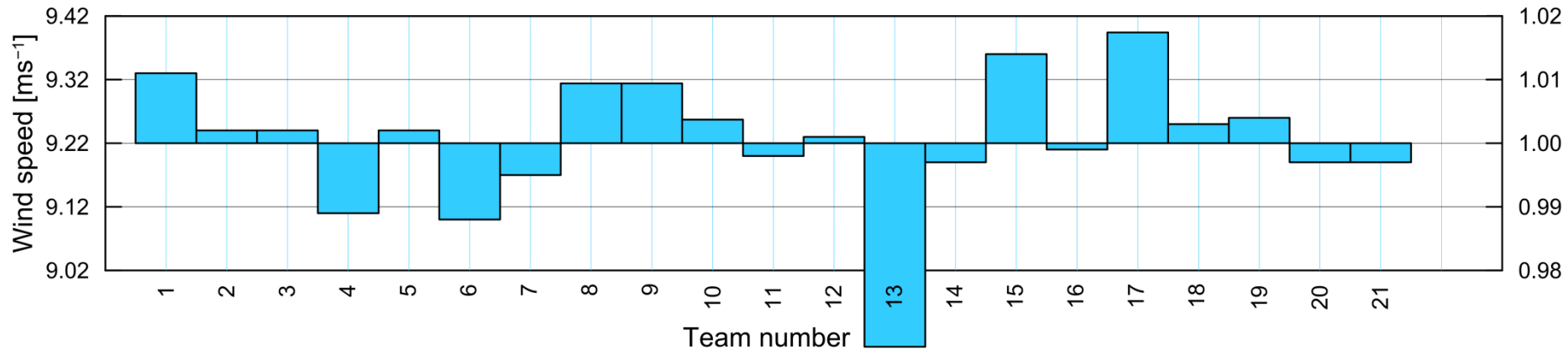
Data points used = 21 (of 22)

Mean wind speed = 9.22 ms^{-1}

Standard deviation = 0.10 ms^{-1}

Coefficient of variation = 1.1%

Range = 8.90 to 9.39 ms^{-1}



Comparison of air density ρ @ hub height

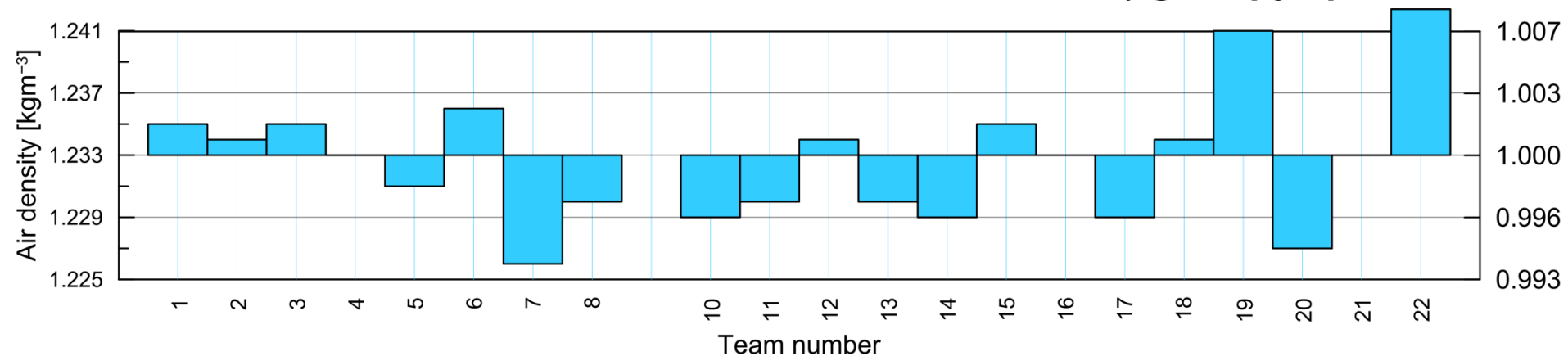
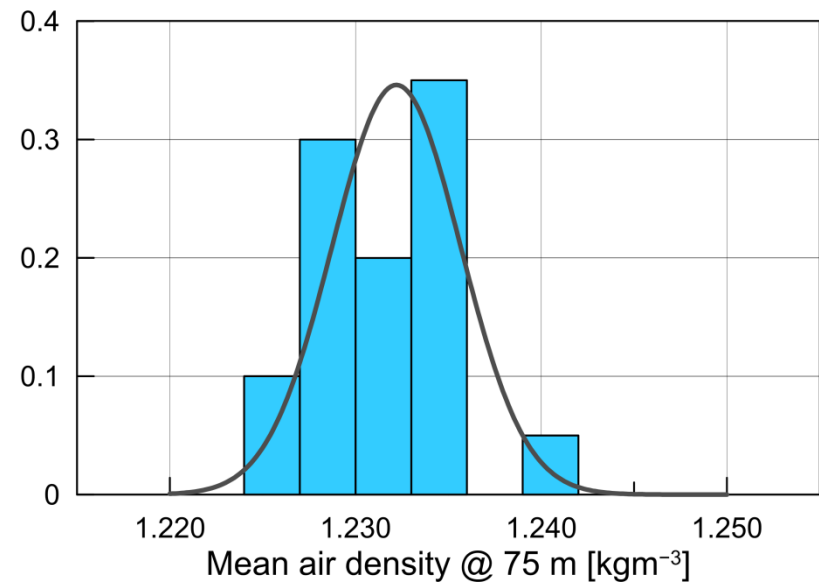
Data points used = 21 (of 22)

Mean air density = 1.233 kgm^{-3}

Standard deviation = 0.004 kgm^{-3}

Coefficient of variation = 0.3%

Range = 1.226 to 1.242 kgm^{-3} (1%)

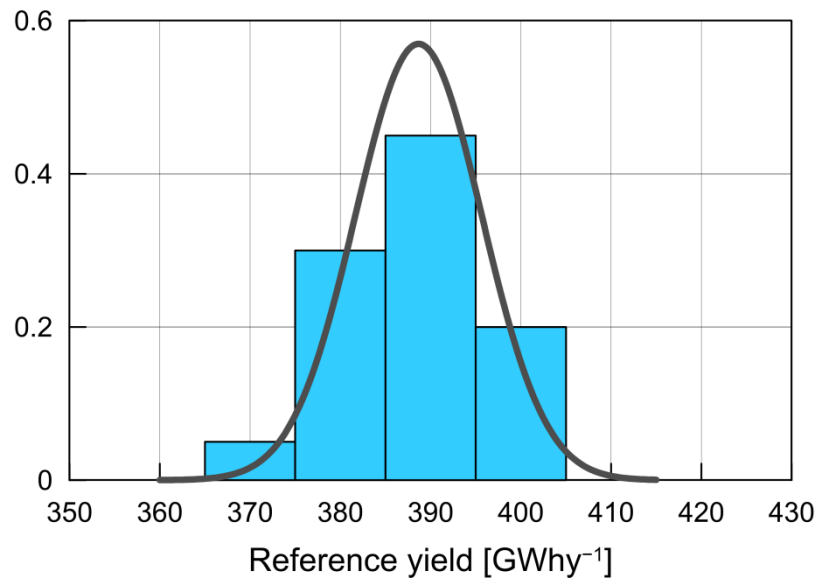


Wind farm key figures – 1 year estimates

Barrow (1 y)		Mean	σ	CV*	Min	Max
Potential yield	GWh	389	7.0	1.8	373	399
Wake loss	%	7.5	1.1	14.8	5.2	9.2
Gross energy yield	GWh	357	10.7	3.0	331	378
Technical losses	%	9.3	0.1	1.0	9.2	9.6
Net energy yield P_{50}	GWh	324	9.6	3.0	300	343
Measured	GWh	308	312			
Difference	%	5.2	3.8			

* Coefficient of Variation in per cent.

Reference yield of wind farm (1 y)



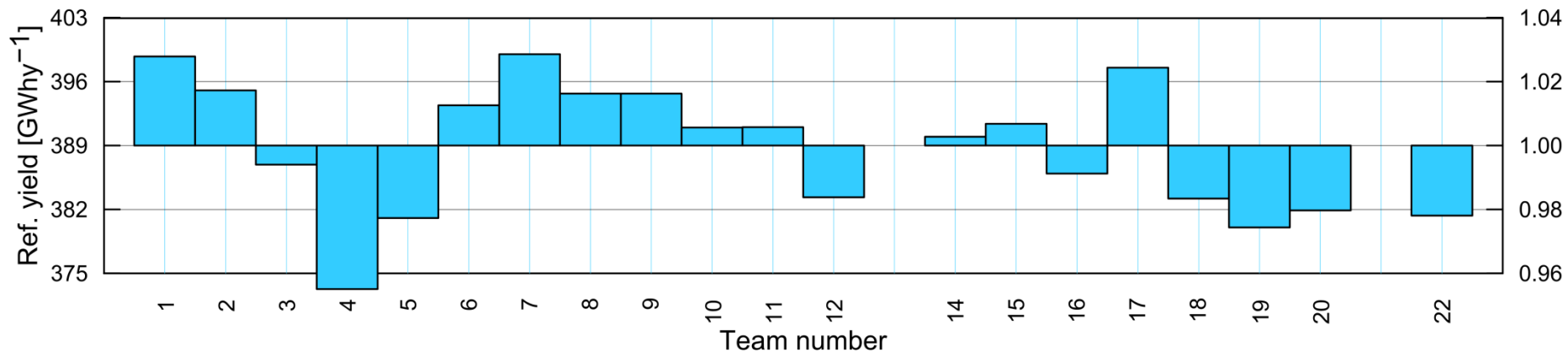
Data points used = 20 (of 22)

Mean net yield = 389 GWhy⁻¹

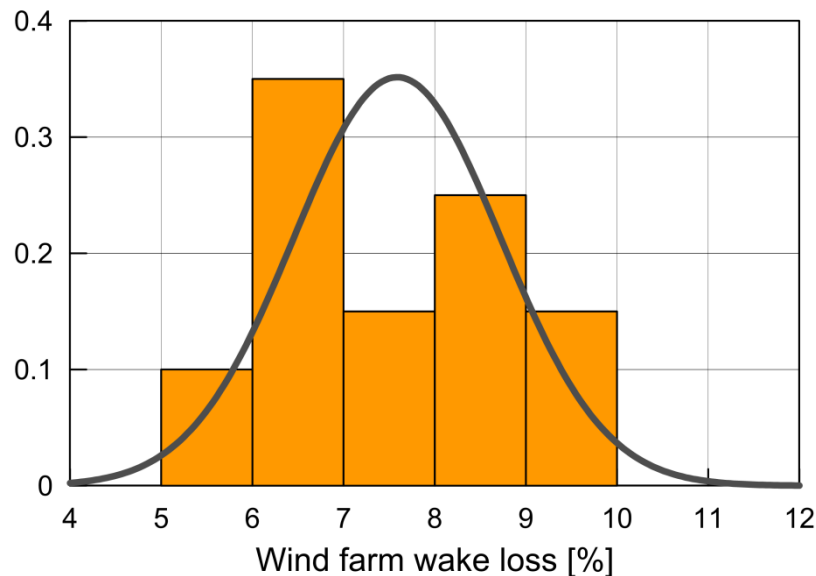
Standard deviation = 7.2 GWhy⁻¹

Coefficient of variation = 1.8%

Range = 373 to 399 GWhy⁻¹



Predicted wind farm wake losses (1 y)



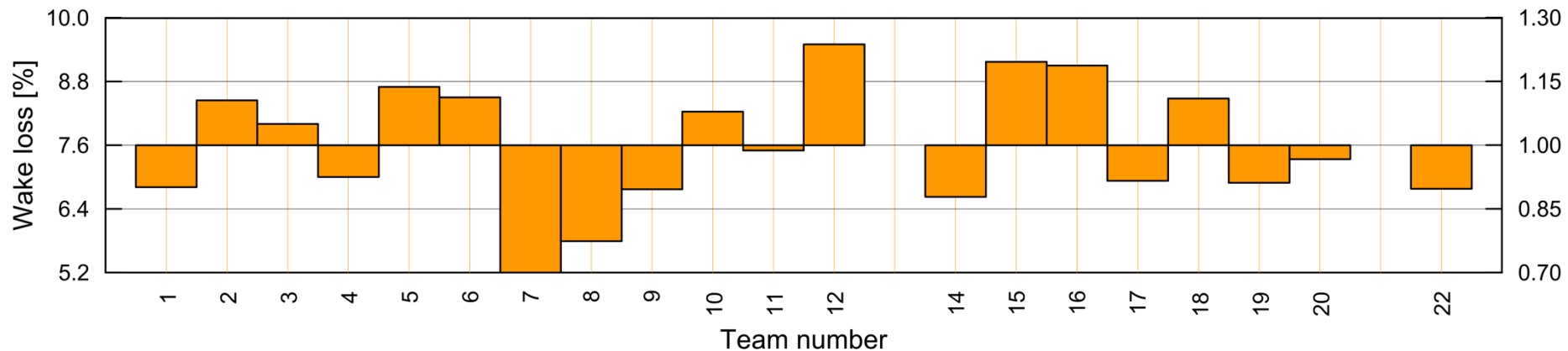
Data points used = 21 (of 22)

Mean wake loss = 7.6%

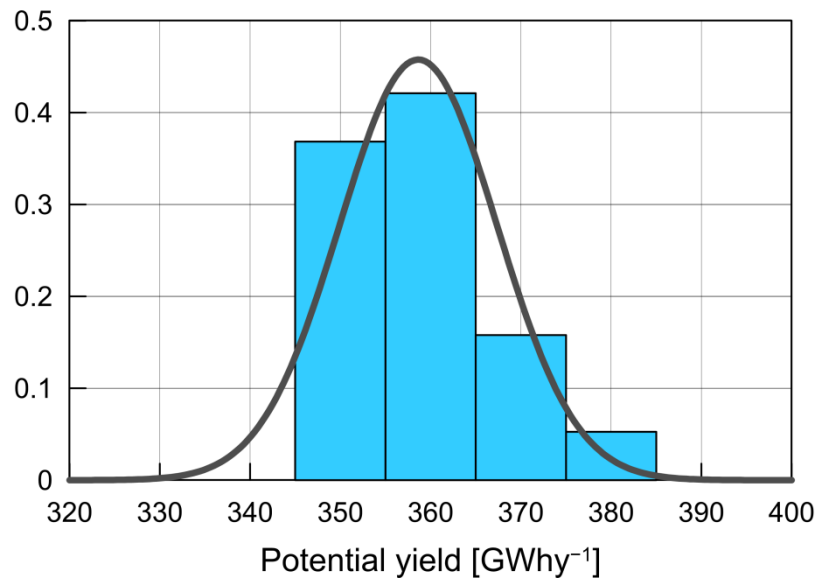
Standard deviation = 1.2%

Coefficient of variation = 15%

Range = 5.2 to 9.5%



Potential yield of wind farm (1 y)



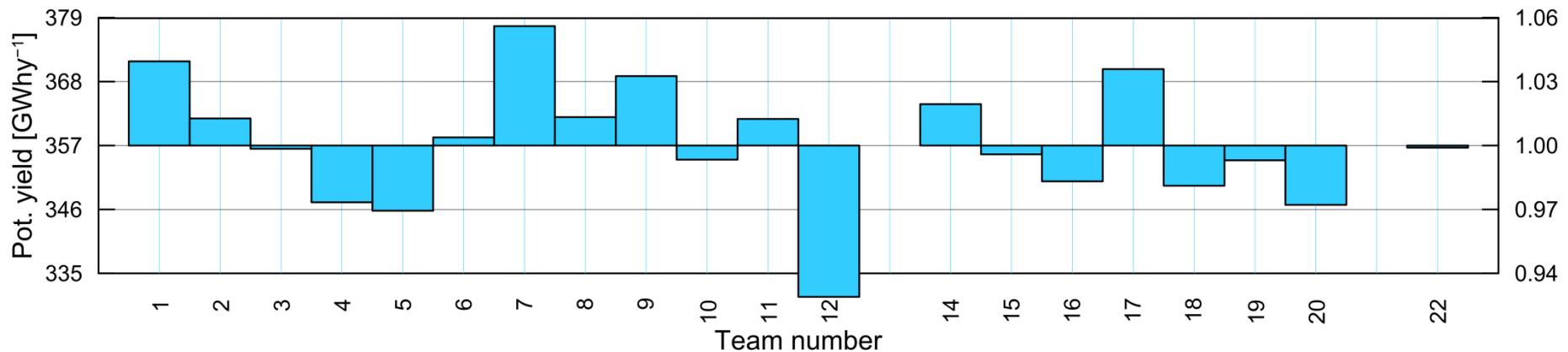
Data points used = 20 (of 22)

Mean net yield = 357 GWhy⁻¹

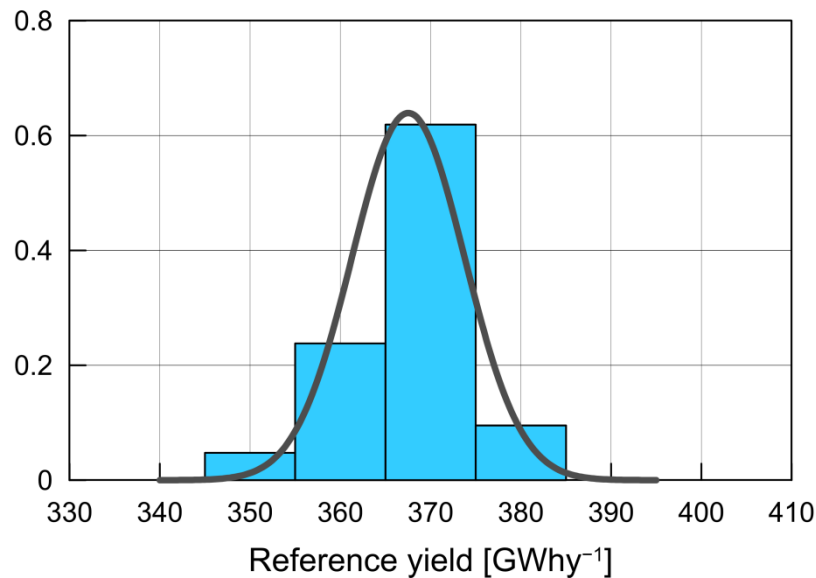
Standard deviation = 10.7 GWhy⁻¹

Coefficient of variation = 3.0%

Range = 331 to 378 GWhy⁻¹



Reference yield of wind farm



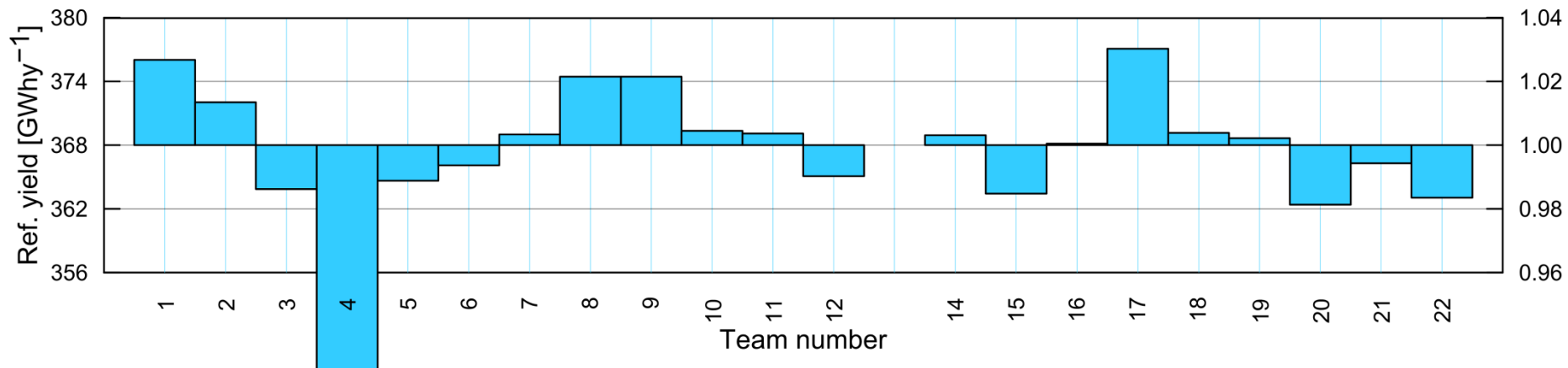
Data points used = 22 (of 22)

Mean reference yield = 368 GWhy⁻¹

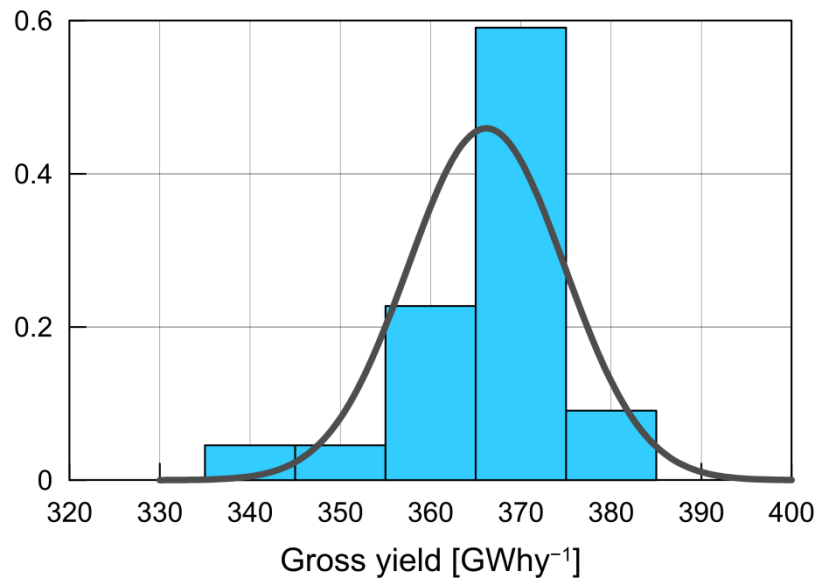
Standard deviation = 6.4 GWhy⁻¹

Coefficient of variation = 1.7%

Range = 347 to 377 GWhy⁻¹



Gross yield of wind farm



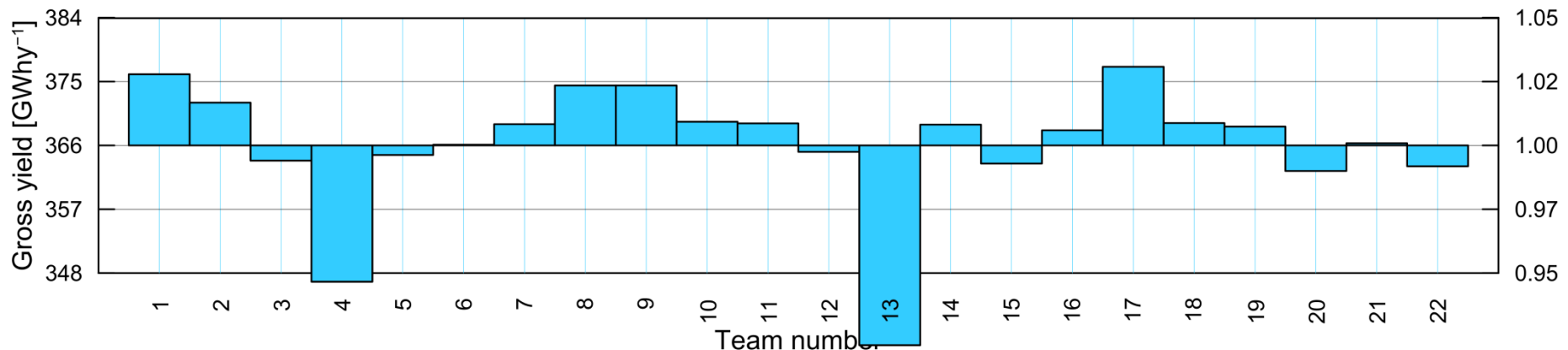
Data points used = 22 (of 22)

Mean gross yield = 366 GWhy⁻¹

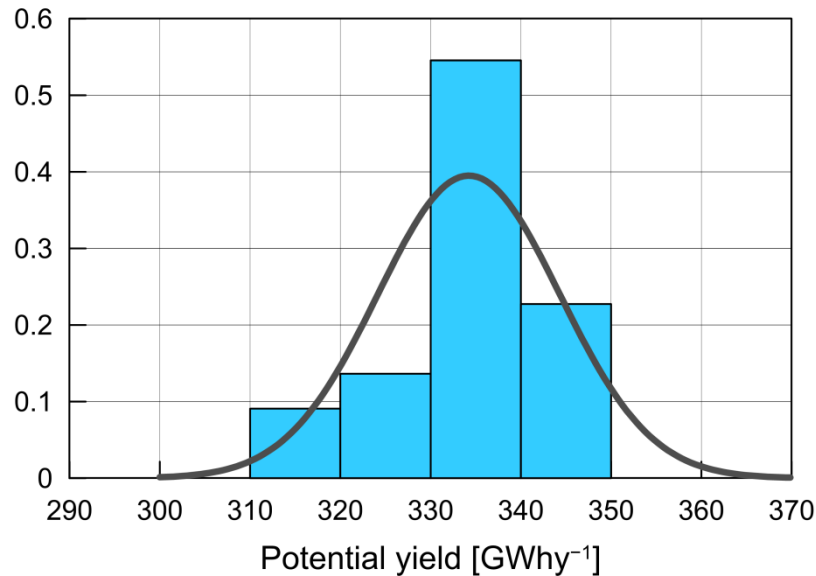
Standard deviation = 8.9 GWhy⁻¹

Coefficient of variation = 2.4%

Range = 338 to 377 GWhy⁻¹



Potential yield of wind farm



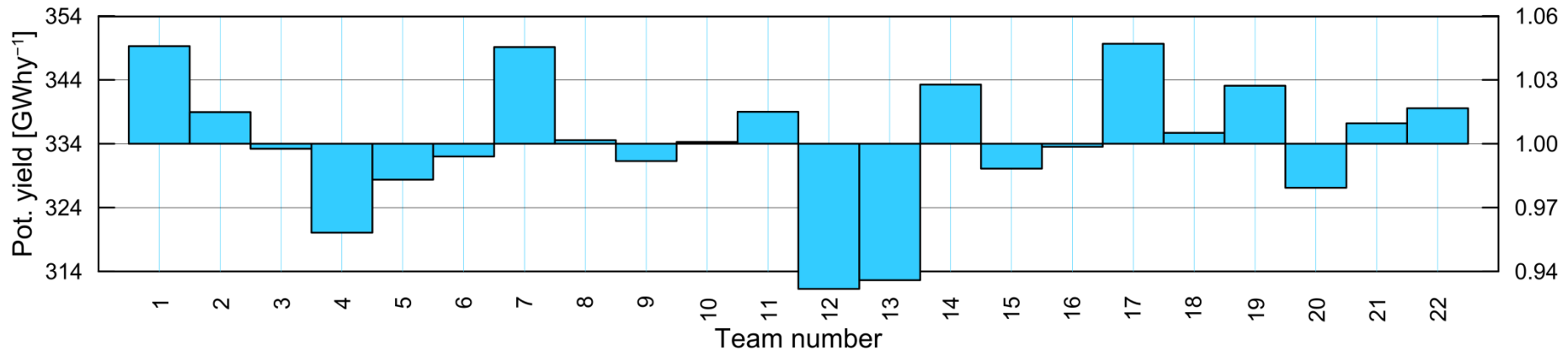
Data points used = 20 (of 22)

Mean potential yield = 334 GWhy⁻¹

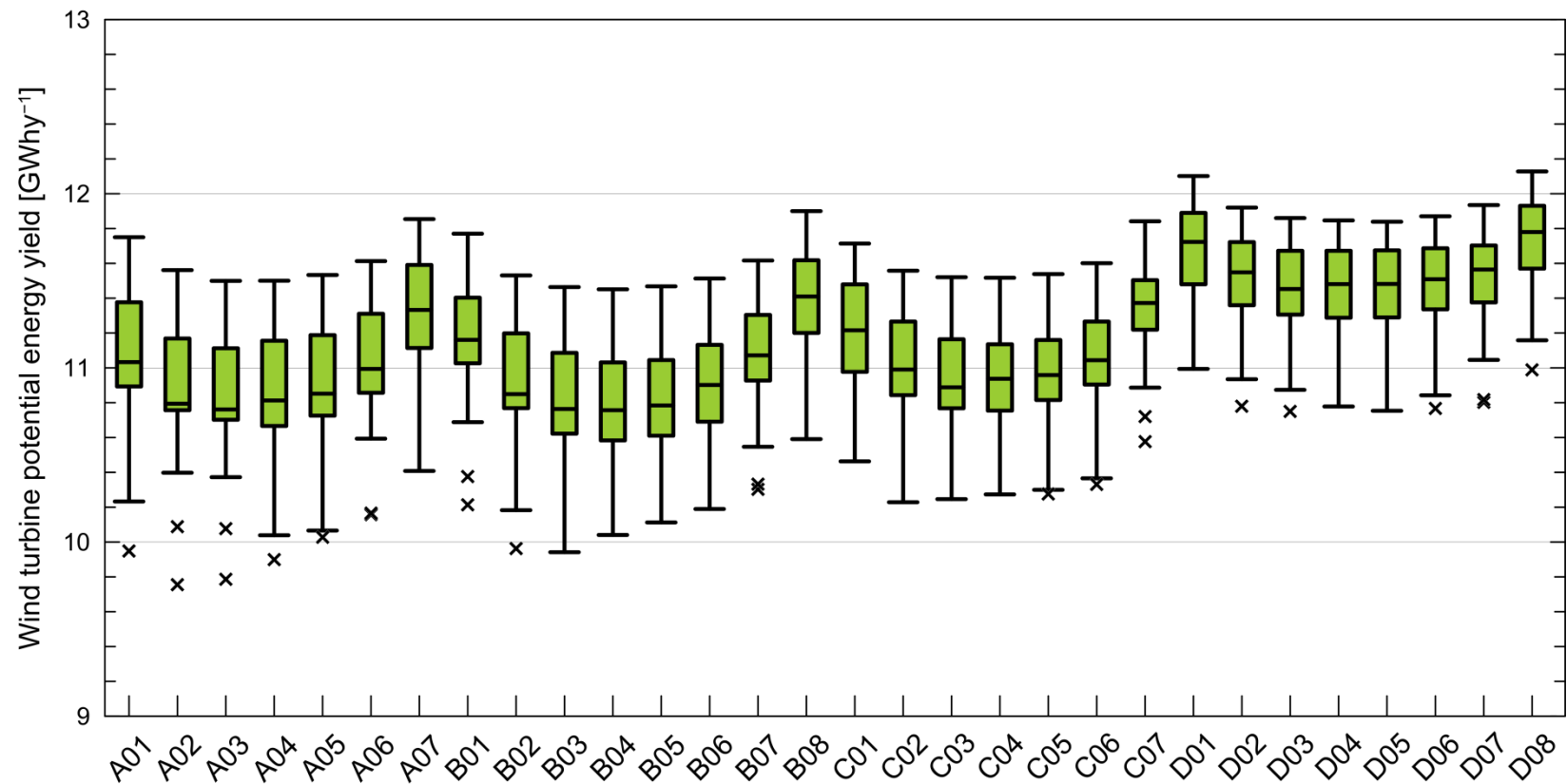
Standard deviation = 10.3 GWhy⁻¹

Coefficient of variation = 3.1%

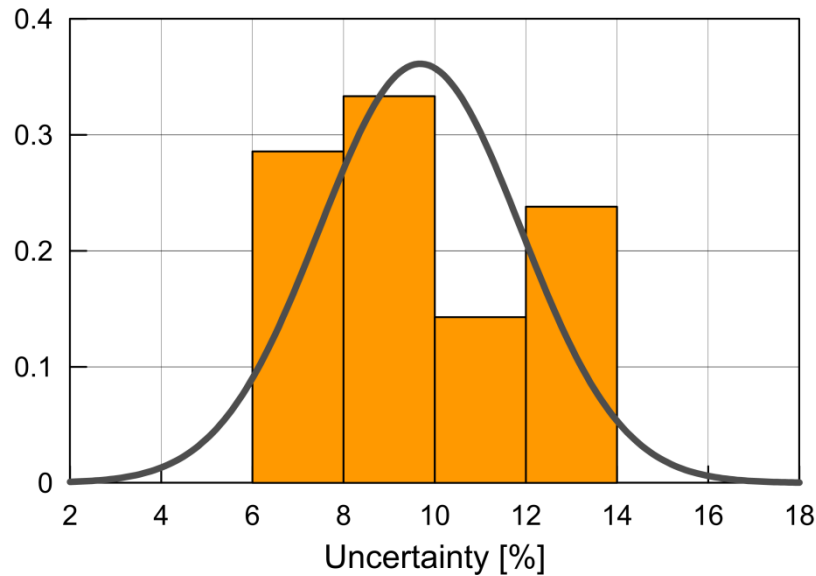
Range = 311 to 350 GWhy⁻¹



Predicted turbine site energy yield



Uncertainty estimates



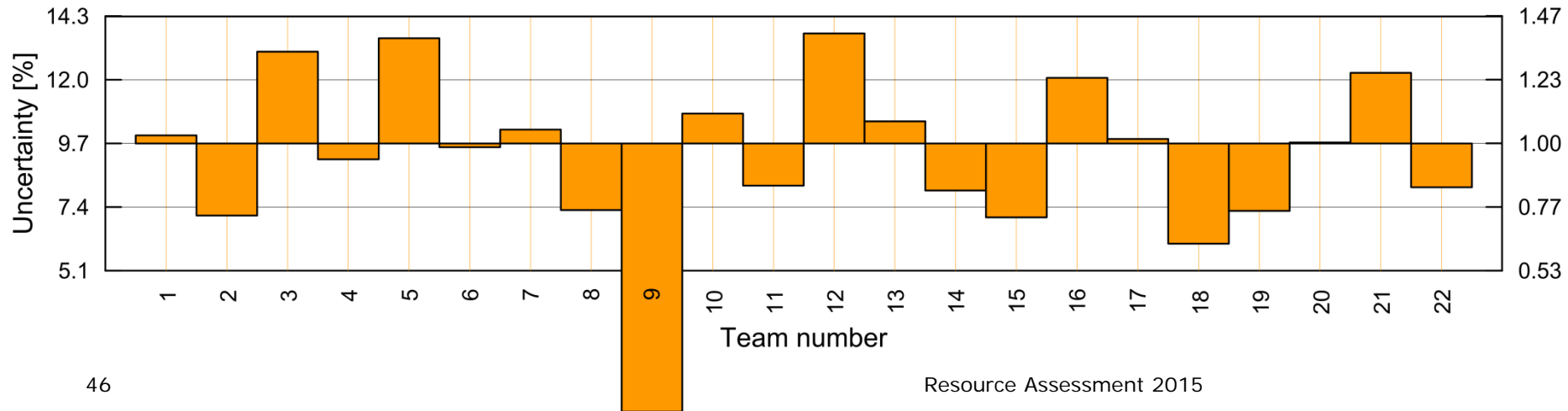
Data points used = 22 (of 22)

Mean uncertainty = 9.7%

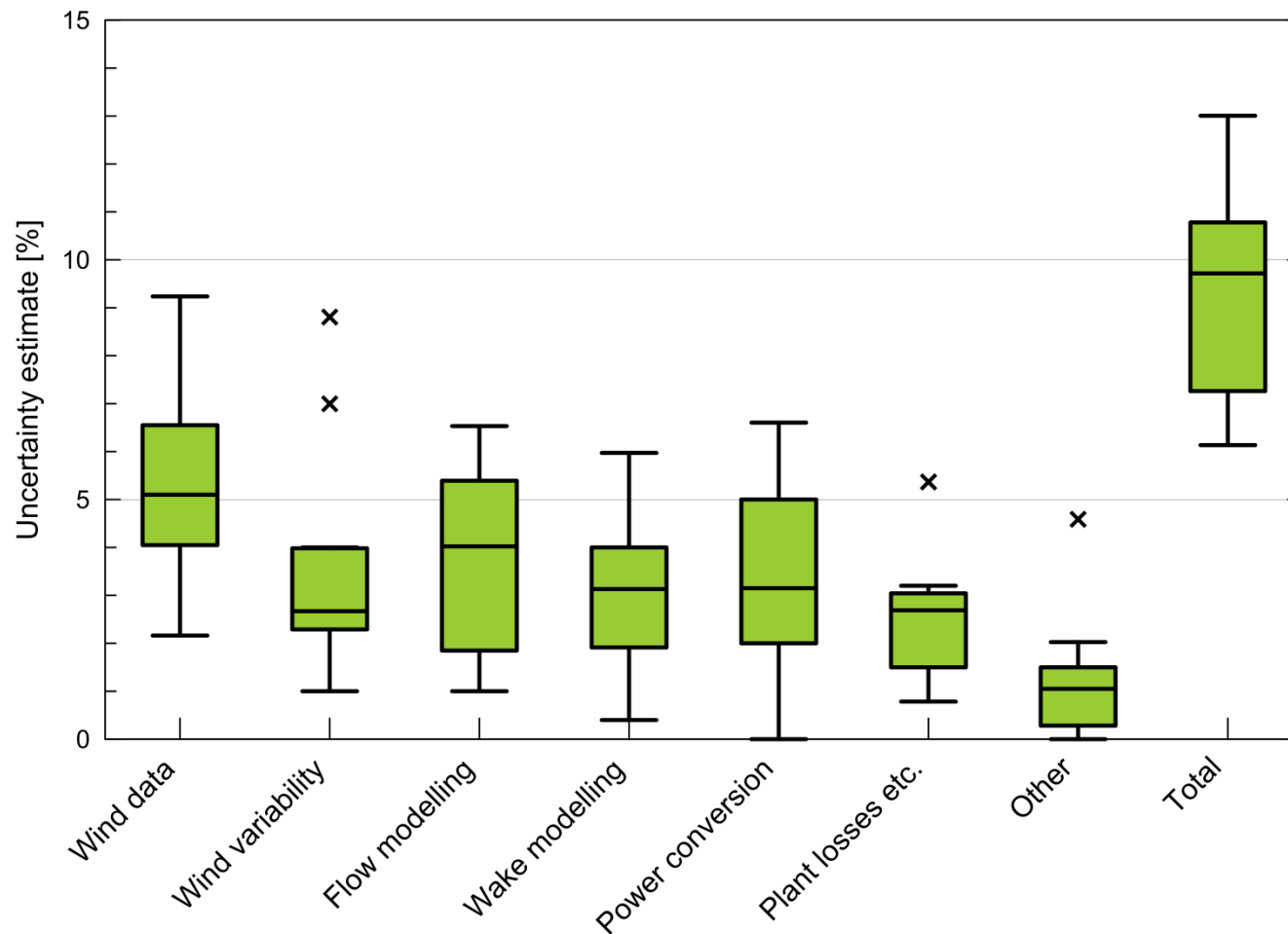
Standard deviation = 2.3%

Coefficient of variation = 23%

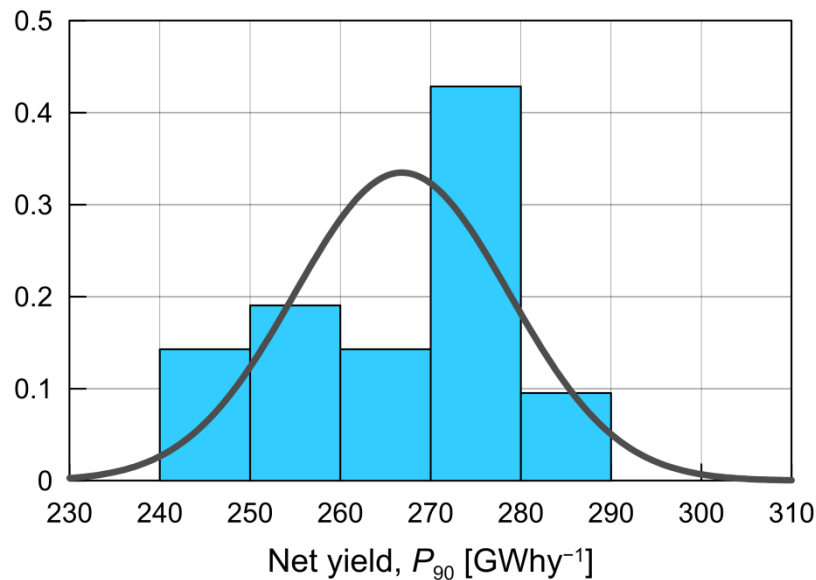
Range = 6.1 to 14%



Uncertainty estimates by type



Net energy yield of wind farm, P_{90}



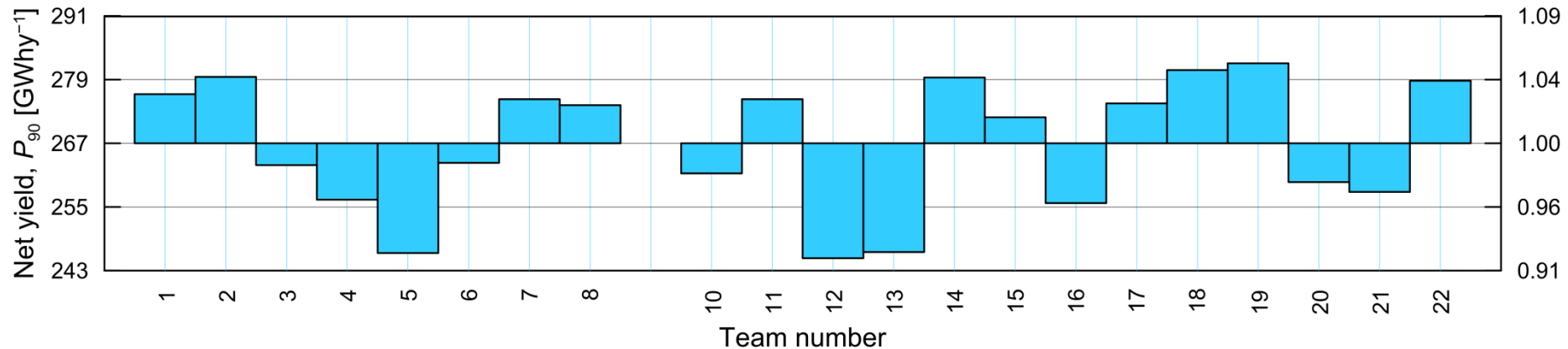
Data points used = 21 (of 22)

Mean net yield = 267 GWh $^{-1}$

Standard deviation = 12.2 GWh $^{-1}$

Coefficient of variation = 4.6%

Range = 245 to 282 GWh $^{-1}$



Profile of participants (the human factor)

What we know

- Number of persons in team
- Number of years in wind power industry
- Type of company
- Approximate number of wind farm projects
- Education as wind energy master or similar
- Continuing education courses in wind energy
- Courses in software tools and models used
- In-house training in wind and yield assessments
- Participation in previous CREYAP exercises

What we would like to show

- What are the main characteristics of the companies and teams?
- Do the team characteristics have a significant impact on the results?
- Which paths do the different teams follow in the prediction process?
- Different calculation practices and tools for production data statistics

Status of work

- No firm conclusions drawn yet
- Work continues and will be reported at a later stage

Legend to graphs

- Results distribution graphs
 - histograms + fitted normal distribution
 - statistics given next to graph
- Team result graphs
 - mean value is base value for histogram
 - y-axis covers a range of ± 2 standard deviations
 - Absolute y-values (left) and relative (right)
 - x-axis covers teams 1-22
 - no team number indicates 'result not submitted'
- Box-whisker plots
 - whiskers defined by lowest datum still within 1.5 IQR of the lower quartile (Q1), and highest datum still within 1.5 IQR of the upper quartile (Q3).
 - Extreme values shown with symbols

References

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Offshore

- Mortensen, N. G., Nielsen, M., & Ejsing Jørgensen, H. (2013). [First Offshore Comparative Resource and Energy Yield Assessment Procedures \(CREYAP\)](#). EWEA Offshore 2013, Frankfurt, Germany, 19/11/13.
- Mortensen, N. G., & Nielsen, M. (2015). [Offshore CREYAP Part 2 – preliminary results](#). European Wind Energy Association (EWEA). EWEA Offshore 2015 Conference, Copenhagen, Denmark, 10/03/15.